A Dissertation for the Degree of Doctor of Philosophy

Greenhouse Gas Emission Factors for Wastewater Treatment and Waste Incineration Facility

폐기물 부문 중 하수처리시설 및 폐기물 소각시설에서의 온실가스 배출계수 개발

August, 2017

By

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Major in Environmental Health, Graduate School of Public Health,

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ABSTRACT

Greenhouse Gas Emission Factors for Wastewater Treatment and Waste Incineration Facility

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Global warming and climate change have become a significant scientific, economic and political issue during the past decade because of increasing greenhouse gases in the atmosphere trap heat. The Intergovernmental Panel on Climate Change (IPCC) reported in 2014 that scientists were more than 95% certain that global warming is mostly being caused by human (anthropogenic) activities, mainly increasing concentrations of greenhouse gases (GHGs) such as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The atmospheric CO_2 level has increased by some 25% since 1850 owing to fossil fuel combustion, irrigation, deforestation, and so on.

The actions of GHG reduction and mitigation in South Korea have implemented in various parts such as economic, political, and social sectors, which the Framework Act on Low Carbon Green Growth was enacted in 2010, with accordance with reducing and mitigating GHG by the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Environment Program (UNEP). Due to policies for reducing GHG, many companies and local governments should calculate and report their greenhouse gases inventories in accordance with guidelines, such as the Intergovernmental Panel on Climate Change (IPCC) guidelines (2006), IPCC Good Practice Guidance and Guidelines of Greenhouse Gas, and Energy Target Management System (TMS) of South Korea.

In order to establish a national inventory report in GHG emissions, the most accurate estimate of emissions should be given priority. Such GHG emission estimates are calculated using activity data (fuel, raw material, and actual usage data) and GHG emission factors in four sectors, which are agriculture, forestry, livestock, food; industry and energy generation; waste; building and transportation. To calculate GHG emissions in these sectors, greenhouse emission factors is required by sectors and when there is no emission factor, the greenhouse gas emissions are calculated by applying the IPCC default values (hereinafter referred to as “default”). In particular, a number of plant-specific emission factors are needed to estimate country-specific emission factors. In order to estimate these emission factors, this study measured GHG emissions from wastewater treatment and waste incineration

facilities, based on plant-specific and operation types. Therefore, this study investigated proper methods for measuring GHGs according to situations of those facilities. The main objectives of this study were (1) to investigate emissions and emission factors from municipal wastewater treatment facility (*Study 1*), (2) to estimate those from waste incineration facilities (*Study 2*), and (3) to assess and compare the emission factors with various other studies (*Study 3*).

For *Study 1*, the GHGs such as CO_2, CH_4, and N_2O are emitted from wastewater treatment processes. The direct emission gases are CH_4 and N_2O, whereas CO_2 is calculated from fossil fuel sources, of which biogenic CO_2 is excluded from wastewater treatment and contained only in indirect use, i.e. energy sources. The CH_4 and N_2O emissions were measured from a municipal wastewater treatment plant (WWTP) in Seoul, using a flux chamber to determine the emission factors. Measurements were performed in the first settling, aeration, and secondary settling basins, as well as in the sludge thickener, sludge digestion tank, and A^2O basins. The total emission factors of CH_4 and N_2O from the activated-sludge treatment were 3.734 g CH_4/kg biochemical oxygen demand (BOD_5) and 1.256 g N_2O/kg total nitrogen (TN), respectively. Those of the advanced treatment (A^2O) were 4.022 g CH_4/kg BOD_5 and 1.605 g N_2O/kg TN, respectively.

For *Study 2*, the flue gas samples were measured at nine South Korea's incineration facilities, i.e. municipal solid waste (MSW), commercial solid waste (CSW), and specified waste (SW), which were operated by different operation types.

Mean of emission factors of municipal solid waste (MSW) were 134 ± 17 kg CO_2 t^{-1}, 88 ± 36 g CH_4 t^{-1}, and 69 ± 16 g N_2O t^{-1}, while those of commercial solid waste (CSW) were 22.56 g CH_4 t^{-1} and 259.76 g N_2O t^{-1}, and for specified waste (SW) incineration emission factors were 2,959 kg CO_2 ton^{-1}, 43.44 g CH_4 t^{-1} and 401.21 g N_2O t^{-1}. Total emissions calculated using annual incineration for MSW were 3,587 ton CO_2-eq yr^{-1} for A facility and 11,082 ton CO_2-eq yr^{-1} for B facility, while those of IPCC default values were 13,167 ton CO_2-eq yr^{-1} for A facility and 32,916 ton CO_2-eq yr^{-1}, thus emissions of IPCC default values were estimated to be higher than those of the plant-specific emission factors and the emission of CSW for C facility was 1,403 ton CO_2-eq yr^{-1}, while those of SW for D–I facilities was 28,830 ton CO_2-eq yr^{-1}. In the sensitivity analysis using a Monte Carlo simulation for emission factors in MSW, the GHG concentrations were found to have a greater impact than incineration and flow rate. For MSW incineration with the same types of stoker in operation, the emissions and emission factors of methane had the opposite trend to those of nitrous oxide when a NO_x removal system was in place, whereas there was no difference in carbon dioxide emissions.

For *Study 3*, greenhouse gas the emission factors presented in various incinerators of many studies have shown significant variations according to country-specific, plant-specific, and operation conditions. CO_2 emission factors of each component for MSW were recalculated in this study from actual measured emissions

from flue gas taking into account fossil carbon content, which the plastics showed the highest fossil carbon content, followed by vinyl and rubber, textiles, inert waste, and paper. Thus, Emission and emission factors in various studies were assessed and compared with other researches of foreign or same countries. Variations of emission and emission factors in those studies were determined by operation types and other conditions of facilities.

In conclusion, emission factors of Tier 2 in wastewater treatment and waste incineration facilities are insufficient of data and have errors of national emission factors in calculating emission inventory for companies, local governments, national inventory report, etc. Therefore, GHG emission factors in this study are helpful for calculating the inventories and needed more studies in the future.

Keywords: greenhouse gases, emission factors, municipal wastewater treatment, waste incineration

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Contents

Chapter 1. Introduction

Chapter 2. Calculation of emission factors for CH_4 and N_2O from the wastewater treatment facility

Chapter 3. Calculation of emission factors for CO_2, CH_4 and N_2O from waste incineration facility

List of Tables

List of Figures

Nomenclature

A	area of the bottom of the chamber, m^2
B_o	Maximum CH_4 producing capacity, kg CH_4/kg BOD
^{14}C	radiocarbon
C_{inlet}	concentration of gas in the air flowing into the chamber
C_{outlet}	concentration of gas in the air flowing out of the chamber
E	greenhouse gas emissions, ton CO_2 yr^{-1}, ton CH_4 yr^{-1}, ton N_2O yr^{-1}
F	Flux, mass $area^{-1}$ $time^{-1}$
FGR_i	flue gas flow rate through the duct, m^3 h^{-1}
i	greenhouse gas, CO_2, CH_4, and N_2O
x	exponential number for the unit conversion
dm	dry matter content
CF	carbon fraction
FCF	fossil carbon fraction
OF	oxidation factor
j	component of the municipal solid waste
Q	flow rate through the chamber, L min^{-1}

Abbreviations and acronyms

A^2O	Anaerobic/Anoxic/Oxic
AFOLU	Agriculture, Forestry and Other Land Use
BOD	Biochemical Oxygen Demand

BURs	Biennial update reports
CFCs	Chlorofluorocarbons
CH_4	Methane
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CSW	Commercial Solid Waste
EF	Emission Factor
FID	Flame Ionization Detector
GC	Gas Chromatograph
Gcal	Giga calories
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWP	Global Warming Potentials
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
KRISS	Korean Research Institute of Standards and Science
LCA	Life Cycle Assessment
MCF	Methane Correction Factor
MSW	Municipal Solid Waste
NCs	National communications
NDIR	Nondispersive infrared sensor
NF_3	Trifluoride
NIR	National Inventory Report
NO_x	Nitrogen Oxide

N_2O	Nitrogen Oxide
OECD	Organization for Economic Cooperation and Development
PE	Population Equivalents
ppb	Parts per billion
ppm	Parts per million
PVC	Polyvinyl Chloride
RSD	relative standard deviation
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SW	Specified Waste
TCD	Thermal Conductivity Detector
TMS	Transportation Management System
TN	Total Nitrogen
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
WF	Waste Fraction
WTE	Waste To Energy
WWTP	Municipal Wastewater Treatment Plant

Chapter 1. Introduction

1.1 Backgrounds for greenhouse gas

In recent years, there has grown an increased awareness of transboundary pollution that places environmental assets at risk both globally and regionally, manmade pollutants have degraded the stratospheric ozone shield, the oceans, the atmosphere, and the biodiversity of the planet; regionally these pollutants have harmed aquifers, rivers, lakes, soils, and forests (Murdoch and Sandler, 1997). Air pollutants produced by human activities that can adversely affect humans and ecosystems can be classified as primary pollutants and secondary pollutants. Primary pollutants produced from a process and emitted directly include particle or gas pollutants, i.e. ash, carbon monoxide, sulfur dioxide, and so on. Secondary pollutants not emitted directly form in the air when primary pollutants react or interact, for example, ground level ozone.

The emission limit of air pollutants in Korea (Atmospheric Environment Conservation Act related to Article 15) is the regulation that administrates particulates, gaseous, nitrogen oxides, sulfur oxides, and certain atmospheric hazardous substances. Furthermore, substances that deplete the ozone layer are entered into force in August 26, 1989 by the Montreal Protocol related with

chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs). Greenhouse gases absorbed and emitted radiation within the thermal infrared range play an important role in the fundamental cause of the greenhouse warming effect and were regulated by beginning the Kyoto Protocol, an international convention for the regulation and prevention of global warming including six types of greenhouse gases, i.e. carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Such anthropogenic emissions of greenhouse gases (GHGs) have led to a considerable increase in the concentrations of these gases in the atmosphere over the past 100 years (El-Fadel and Massoud, 2001). The United Nations Framework Convention Climate Change (UNFCCC) is the globally recognized platform for collective action on the reduction of anthropogenic GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) formulated a guideline in 1996, 2006, and Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (hereinafter referred to as "GPG 2000") to account for GHG emissions and mitigate against global climate change in four general sectors (energy; industrial processes; agriculture, forestry and other types of land use; and waste; Foley et al., 2010).

In addition to economic growth, the National Oceanic and Atmospheric Administration (NOAA) scientists reported that the concentration of CO_2 in the air increases to more than 400 parts per million by volume, compared to about 280 ppm in pre-industrial times. The global surface temperature is likely to rise a further 0.3

to 1.7 ℃ (0.5 to 3.1 ℉) for the lowest emission scenario and 2.6 to 4.8 ℃ (4.7 to 8.6 ℉) for the highest emission scenario by the IPCC for its fifth Assessment Report (AR5) during the 21st century. Furthermore, the Paris Agreement was adopted in 2015, i.e. 21st yearly session of the Conference of the Parties (COP) in Paris had agreement on the reduction of GHG to set a goal of limiting global warming to less than 2 ℃ compared to pre-industrial levels.

According to the International Energy Agency's 'CO_2 Emissions from Fuel Combustion Highlight 2016' report, worldwide CO_2 emissions (138 countries) from fossil fuel combustion were 20,503 million tons in 1990 and 32,381 million tons in 2014, an increase of 1.6 times in 2004 compared to 1990. In Korea, CO_2 emissions from fossil fuel combustion amounted to 231.7 million tons in 1990, 17th in the world. In 2014, it was 7th in the world with 567.8 million tons. At present, the GHG emissions of developed countries are stagnant, and the emissions of developing countries have increased, exceeding those of developed countries. CO_2 emissions per capita are high in developed countries, but those of emissions per gross domestic product (GDP) are high in developing countries. In recent 20 years, Korea's CO_2 emission rate has been the fastest among the Organization for Economic Cooperation and Development (OECD) member countries. In keeping with the Paris Agreement dealing with greenhouse gases emissions mitigation, adaptation and finance starting in the year 2020, the government and the industries in Korea are preparing various policy and reduction activities in preparation for the new

post-2020 system. In addition, Korea's low carbon green growth strategy was enacted on January 13, 2010, which related with regulations to reduce greenhouse gas emissions from industries, incentive mechanisms for businesses to develop green technologies and products, and public information tools to increase awareness and demand for green products. Furthermore, Greenhouse gas Inventory and Research Center of Korea is a national greenhouse gas information hub and a sink tank for greenhouse gas, established to contribute to low carbon green growth. The roles are as follows: establishment of a GHG statistical management plan, preparation of a national inventory report (NIR), construction and operation of a national greenhouse gas management system, offset registration system, establishment and operation of national GHG reduction roadmap, support for stable operation of GHG emission trading system, implementation evaluation system of emission trading system, advancement of emission trading system through international cooperation, and so on. Therefore, national greenhouse gas emission surveys should be preceded in order to implement GHG reduction and adaptation.

Based on the Framework Act on Low Carbon Green Growth in Korea, the national inventory report is needed. GHG emission inventories should be presented to the Government, which companies, local government and other facilities that exceed emission standards should write those inventories in accordance with the national guideline. Measuring, reporting and verifying (MRV) were established in four sectors, which were agriculture, forestry, livestock, food; industry and energy

generation; waste; building and transportation. In order to write those inventories, the most basic approach to estimating GHG emissions is to comply with 1996, 2006 Guidelines and IPCC Good Practice Guidance, which uses to combine information on the extent to which a human activity takes place (called activity data) with coefficients which quantify the emissions or removals per unit activity, so called emission factors (EF) by 2006 IPCC guidelines. A tier concept represents a level of methodological complexity, which usually used the three tiers concepts. Tier 1 is the basic method and designed to use readily available national or international statistics in combination with the provided default emission factors and additional parameters that are provided for all categories and therefore should be feasible for all countries by 2006 IPCC guidelines. Tier 2 is intermediate method, which combined with default emission factors of IPCC guidelines and country-specific emission factors. Tier 3 is higher complexity method using plant-specific emission factors. Tier 2 and 3 are sometimes referred to as higher tier method and are generally considered to be more accurate (IPCC, 2006). Tier 4 is a method using the emission factors by the continuous monitoring system.

According to the National Inventory Report (2016) in Korea, total GHG emissions in 2014 were 690.6 million tons of CO_2-eq, which increased by 135.6% from the total of 293.1 million tons of CO_2-eq in 1990 and decreased by 0.8% of the total emissions of emissions of 696.5 million tons of CO_2-eq in 2013, respectively. GHG emissions in the waste sector in 2014 amounted to 15.4 million tons of CO_2-eq,

accounting for 2.2% of total national emission, an increase by 47.8% compared to 1990 and decreased 3.3% from 2013. In waste sector, emission portion of waste landfill accounted for 47.5%, waste incineration was 41.1%, wastewater treatment was 9.2%, and other sector was 2.2%. Furthermore, in the incineration facilities, GHG emissions of incineration facilities where energy is recovered are calculated in the energy sector, and those of the facilities in which energy is not recovered are calculated in the waste sector.

As mentioned above, what are of primary importance in estimating national emissions is activity data (such as fuel and raw material usage) and emission factors. In order to estimate the GHG emission factors in this study, wastewater treatment plant and incineration facilities were set up in the waste sector, and the emission factors for each facility were calculated from those GHG emissions.

In this study, Greenhouse gas emissions and emission factors were measured at a wastewater treatment plant and nine incineration facilities. In the wastewater treatment plant, all the basins were measured with the activated sludge treatment process and the advanced treatment process. Furthermore, the GHGs such as CO_2, CH_4, and N_2O are emitted from wastewater treatment processes. The direct emission gases are CH_4 and N_2O, whereas CO_2 is calculated from fossil fuel sources, of which biogenic CO_2 is excluded from wastewater treatment and contained only in indirect use, i.e. energy sources. On the other hand, incineration facilities are included the GHGs such as CO_2, CH_4, and N_2O, which CO_2 gas is generated from anthropogenic

sources. In the incineration treatment facilities, greenhouse gases were estimated at municipal solid waste incineration, commercial solid waste incineration, and specified waste incineration facilities. Such emission factors of estimation at the workplace can be the basis to devise methods of proper measuring GHG and characterize emission factors for basis data (Tier 2) of national emission factors. Furthermore, the limitation of this study and future directions for the measuring the GHG emissions and calculation the emission factors in wastewater treatment plants and incineration facilities were also discussed.

1.2 Greenhouse gas emission factors from wastewater facility

Greenhouse gases (GHG) are being discharged in a variety of sectors and numerous studies have been conducted on the emissions of methane (CH_4) and nitrous oxide (N_2O) from various sources (e.g., landfills, wetlands, wastewater treatment plants; Daelman et al., 2013). The GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are emitted from wastewater treatment processes. Centralized wastewater treatment system can be collected and transported by a network of pipes and pump stations to municipal wastewater treatment plants, while decentralized wastewater treatment system or on-site system (such as septic tank, biofilters, and aerobic treatment systems) can be treated on a small scale. Centralized system can be classified as primary, secondary, and tertiary treatment process. In the primary treatment, the settled and floating materials are removed, and secondary treatment process consists of a combination of biological treatment by biodegradation of water-borne micro-organisms in a managed habitat (IPCC, 2006). Tertiary treatment processes are used to further purify the wastewater of pathogens, contaminants, and remaining nutrients such as nitrogen and phosphorus compounds. Sludge is produced in all of the primary, secondary and tertiary processes of treatment, which reduce the amount of organic matter including anaerobic digestion, aerobic digestion, and composting.

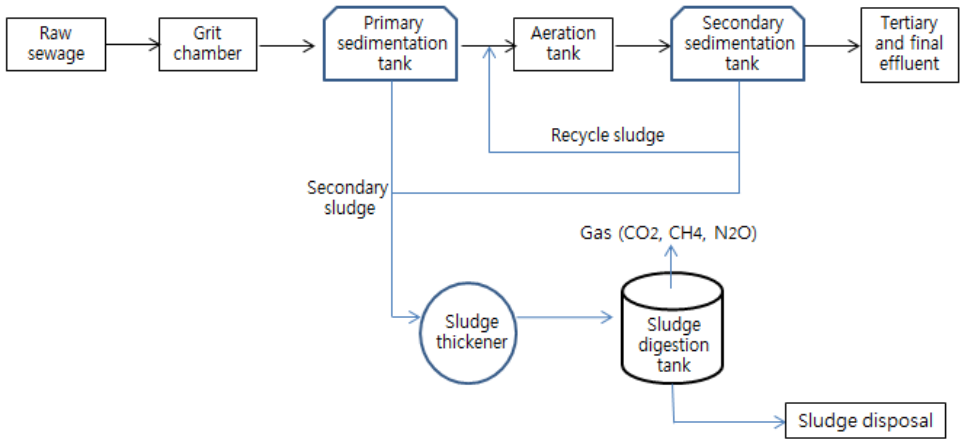

Fig. 1.1. Diagram of a wastewater treatment plant.

There is an increasing need to reduce these emissions and to identify the factors controlling the GHG emissions from wastewater treatment plants (Kampschreur et al., 2009). CO_2 emissions are biogenic origin source, thus should be excluded from the total emissions, whereas CH_4 and N_2O emissions should be contained total emission inventory in wastewater sector.

CH_4 in the wastewater treatment was emitted by degrading anaerobically, which was influenced by temperature, organic materials, and operational conditions. General parameters were the biochemical oxygen demand (BOD) for aerobic organic materials and chemical oxygen demand (COD) to measure the organic component of the wastewater using for biodegradable and non-biodegradable industrial wastewater.

N_2O can be produced in wastewater process by nitrifying and denitrifying bacteria under aerobic or anaerobic conditions (Duan et al., 2015). CH_4 emission from WWTPs occurs mainly from anaerobic decomposition by activating methanogens, as well as from the anaerobic digestion of wastewater sludge. Furthermore, CH_4 can be collected and used as an energy source, indirectly reducing CO_2 emissions (Oshita et al., 2014); however, few studies have been conducted on the CH_4 and N_2O in wastewater treatment except the research on the anaerobic digestion of sewage sludge (Wang et. al., 2011). Therefore, WWTPs are recognized as one of the major sources of GHG emissions (Yan et al., 2014).

In the IPCC methodology, many factors such as B_o, MCF, total organic materials, and population were needed to estimate GHG emissions (see Appendix). In this study, regardless of the factors proposed by the 2006 IPCC, the plant-specific emission factors were calculated to measure the GHG emission by multiplying the activity data by the emission factors of the wastewater treatment plant.

CH_4 and N_2O emissions were investigated from the Jungryang municipal wastewater treatment plant in Seoul to calculate the emission factors from each basin, including the wastewater sludge anaerobic digestion and anaerobic/anoxic/aerobic (A_2O) processes. In addition, there have been few studies on the emissions and emission factors of each process unit based on the biochemical oxygen demand (BOD_5) and total nitrogen (TN) in WWTPs in Korea, including those for the anaerobic digestion tank used for the sludge after settling (Fig 1.1).

To estimate the emissions, a flux chamber system, which can sample gaseous emissions from a defined surface area of the source, was used to measure the concentrations of the fluxes of various gases (Leyris et al., 2005). In the sewage treatment plants, odor occurs during the anaerobic treatment. In order to reduce and eliminate those odors, a cover structure is used if possible. In the primary and secondary sedimentation, the tanks or basins are usually equipped with mechanically driven scrapers that continually drive the collected sludge towards a hopper in the base of the tank where it is pumped to sludge treatment processes. Because of such roof coverings and scrapers for eliminating substances, passive chamber system for

measuring the GHG has created in the wastewater treatment plants. In addition, it is not easy to stabilize the gas chromatograph (GC) due to the moving scraper of the sewage treatment plant, while the GC equipment is needed more stabilization time for analyzing for measuring GHG. Therefore, gas of the Tedlar bags that used the pump to inhale the GHG in the chamber over the wastewater surface was analyzed by the GC in the laboratory as soon as possible.

The CH_4 and N_2O emission factors were calculated by converting the concentration into the BOD and TN of inflow and outflow, and wastewater quantities of the treatment basins, which sampling sites were on surface of the primary settlement, aeration, secondary basins for the activated sludge treatment process, and tertiary treatment basins (anaerobic/anoxic/aerobic reactor). In addition, sludge digestion tank was implemented for the CH_4 and N_2O emission factors.

In this study, CH_4 and N_2O emission factors were calculated for the view of Tier 3, the higher methodology described in the IPCC guidelines using plant-specific emission factors, which detailed estimates were given in Chapter 2.

1.3 Greenhouse gas emission factors from waste incineration facility

A large amount of waste is being generated due to economic development, population growth, and increased consumption. Waste incineration as a waste disposal method is increasing in popularity worldwide due to the lack of land and the potential for soil and water pollution associated with landfilling, as well as the added benefit of the potential for energy recovery from incineration (Harris et al., 2015).

Incineration has a lot of pollutants such as non-volatile organic compounds, particulate matter, heavy metals, dioxins, furans, sulfur dioxide, carbon monoxide, nitrogen oxides, ash, and other pollutants. Air pollutants are regulated by the Air Quality Preservation Act in Korea and greenhouse gas, the leading cause of climate change, is also being managed by the Greenhouse gas Inventory and Research Center of Korea.

Greenhouse gases (GHGs) emitted in the waste incineration processes include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which emissions of CO_2 being more significant than those of CH_4 and N_2O emissions (IPCC, 2006). Under the United Nations Framework Convention of Climate Change [UNFCCC; UN (1992)], these GHGs should be reported in a national inventory report (NIR).

By 2012, the production of household and industrial waste had increased to 49,000 and 146,000 tons per day, respectively, that is, an increase of approximately 1.5 times for industrial waste. In addition, emissions from the waste sector were 14.8 million tons of CO_2 equivalent (CO_2 eq) in 2012, accounting for 2.2% of the total emissions in South Korea. This was a 49.4% increase from the 1990 level and a 1.6% increase from the 2011 level (GGIRCK, 2014). In 2014, waste generation was approximately 388,000 tons per day and the recycling rate was 84.8%, which represented a 0.9% increase from the 2013 level (landfill: 9.1%, incineration: 5.8%, other: 0.3%) (MOE, 2015).

Incineration types include municipal solid waste (MSW), commercial solid waste (CSW), industrial waste, hazardous waste or specified waste, clinical or medical waste and sewage sludge. Operation types of incineration have fixed grate, rotary-kiln, fluidized bed, specialized incineration such as mixed types of incineration. During the incineration of fossil fuel materials, emissions of CO_2 are more significant than CH_4 and N_2O emissions. Emissions of GHG from incineration vary owing to the different parameters that influence emission levels such as fossil fuel content, operation types, de-NO_x system, technology for incineration and conditions during the incineration process. Normally, N_2O is affected by emissions depending on the de-nitrogen system. Such denitrification system and nitrogen oxide removal technologies include selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and complex denitrification system. SCR system

has reductant such as ammonia and urea, which adsorbed onto a catalyst (such as vanadium, molybdenum, tungsten, zeolites, or various precious metals) at a temperature zone (250–350 ℃). SNCR system has reductants in an aqueous solution (such as ammonia water or urea) or in gaseous form (ammonia) without catalysts at a higher temperature zone (900–1100 ℃). SNCR has lower installation cost than SCR, and has low denitrification efficiency, while SCR has high denitrification efficiency and low ammonia slip to the flue gas resulting in low NO_x emission. The complex denitrification system uses both SCR and SNCR simultaneously to eliminate problems of SCR in low load, which installed SNCR at the front end and SCR at the rear end. Especially, depending on which de-NO_x system is installed, it affects N_2O gas emissions.

Emissions from waste incineration without energy recovery are reported in the Waste Sector, while emissions from incineration with energy recovery are reported in the Energy Sector, both with a distinction between fossil and biogenic carbon dioxide (CO_2) emissions (IPCC, 2006). CO_2 emissions from oxidation, during incineration in waste of fossil carbon (such as plastics, certain textiles, rubber, liquid solvents, and other fossil materials) are considered net emissions for CO_2 emission estimate, while those of biomass materials (such as paper, food, and wood waste) should not be included in total emissions. CO_2 emission estimate based on the total amount of waste combusted is as follows:

$$CO_2\ Emissions = \sum_i (SW_{i,j} \times dm_{i,j} \times CF_{i,j} \times FCF_{i,j} \times OF_{i,j}) \times 44/12 \quad (1.1)$$

Where:

CO_2 Emissions = CO_2 emissions in inventory year, Gg/yr

SW_i = total amount of solid waste of type *i* (wet weight) incinerated, Gg/yr

dm_i = dry matter content in the waste (wet weight) incinerated, (fraction)

CF_i = fraction of carbon in the dry matter (total carbon content), (fraction)

FCF_i = fraction of fossil carbon in the total carbon, (fraction)

OF_i = oxidation factor, (fraction)

44/12 = conversion factor from C to CO_2

i = type of waste incinerated specified

j = component of the MSW incinerated such as paper/cardboard, textiles, food waste, wood, garden (yard) and park waste, disposable nappies, rubber and leather, plastics, metal, glass, other inert waste.

CO_2 emissions from waste incineration facilities were from flue gas measured directly for sampling and fossil carbon content were considered. CH_4 and N_2O emissions from incineration are generated in the incomplete combustion and usually very small. CH_4 emission estimate based on the amount of waste combusted is as follows, which the following equation is equal in Appendix equation:

$$CH_4\ and\ N_2O\ Emissions = \sum_i (IW_{i,j} \times EF_{i,j}) \times 10^{-6} \quad (1.2)$$

Where:

CH_4 and N_2O Emissions = CH_4 and N_2O emissions in inventory year, Gg/yr

IW = amount of solid waste of type *i* incinerated or open-burned, Gg/yr

EF = aggregate CH_4 and N_2O emission factor, kg CH_4 and N_2O/Gg of waste

10^{-6} = conversion factor from kilogram to gigagram

i = category or type of waste incinerated

j = component of the MSW incinerated such as paper/cardboard, textiles, food waste, wood, garden (yard) and park waste, disposable nappies, rubber and leather, plastics, metal, glass, other inert waste.

In this study, CO_2 emissions and emission factors were calculated by plant- specific (SW, dm, and CF) and IPCC default values (FCF, OF), which oxidation factor (OF) is a value that assumes 100% complete combustion (1.0). Greenhouse gas measurements were conducted at two municipal solid waste (MSW), one commercial solid waste (CSW), and nine specified waste facilities, which details are given in Chapter 3. Sampling was performed by attaching a sampling pipe to a chimney, connecting a cooling device and a portable flow pump, and sampling at a constant speed. It is necessary to measure the flow rate of exhaust gas, temperature, and water content of the exhaust gas (The test method of Ministry of Environment (MOE), 2004 and US EPA method (South coast air quality management district, Method 10.1, 1989).

1.4 Objectives

In order to reduce these greenhouse gases, many efforts are implemented in various countries around the world. It is necessary to know the greenhouse gas emission for GHG reduction. The national inventory report of Korea is being produced and GHG statistics are divided into energy, industrial process, agriculture, Land use/Land-Use Change and Forestry, and waste sectors, which the estimation needed of activity data and emission factors. In addition, currently, emission factors of national values for Tier 2 are insufficient for each sector.

Wastewater treatment can also produce greenhouse gases in process of biological treatment and waste incineration facilities produce greenhouse gases with containing fossil carbon, e.g. plastics, are the most important sources of CO_2 emissions. Moreover, there is insufficient of estimation for emission factors in wastewater treatment plants and incineration facilities in the waste sector in Korea.

Wastewater treatment facilities and incineration facilities use national emission factors to estimate greenhouse gas emissions. However, national emission factors in wastewater treatment facilities are in error and need to be revised in the future. In addition, the national emission factors in incineration facilities are divided into municipal waste and industrial waste, which needs to be divided into more granular waste components to modify the emission factors.

In the incineration facilities, the emission factors showed a large deviation in studies. Kim et al. (2010) estimated the emission factors from the emissions calculated by IPCC method (Tier 2a and Tier 2b), and MOE (2000, 2002) used carbon content not fossil carbon content, which overestimated for CO_2 calculation of emission factors. Furthermore, the N_2O emission factor of industrial waste in NIR of Korea also used in construction and specified waste, and CH_4 emissions were not calculated in all kinds of waste facilities because of methodology of GPG 2000 related with negligible gas. The emission factor variation may be large depending on waste components, and it was affected by various parameters by methodologies, operation types of incinerators, condition of operation, measuring method for equipment, etc. Therefore, national emission factors need to be developed for waste component and operation type based on the more emission factors from plant-specific data.

Thus, the main objective of this study was to measure the greenhouse gas emissions and estimate emission factors. Following are the specific research objectives:

(1) To measure CH_4 and N_2O emissions and calculate emission factors by dividing emissions by the activity data (BOD and TN) at the municipal wastewater treatment plant (Chapter 2), without applying IPCC default values as mentioned above

(2) To measure CO_2, CH_4,and N_2O emissions and calculate emission factors at the municipal solid waste, commercial solid waste, and specified waste incineration facilities (Chapter 3), with considering fossil carbon content for CO_2

(3) To assess and compare with other studies and suggest deficiency and assignment according to this study and other researches, and discuss the limitation of this study and future directions for the measuring the GHG emissions and calculation the emission factors in wastewater treatment plants and incineration facilities (Chapter 4)

This dissertation is divided into five chapters. Chapter 1 is primarily description of the climate change and GHG emissions for background to this study. Chapter 2 presents the methodological process and results of greenhouse gas emissions and emission factors at the municipal wastewater treatment plant. Chapter 3 presents methodological process and results of greenhouse gas emissions and emission factors at the municipal solid waste, commercial solid waste, and specified waste incineration facilities. Chapter 4 presents the comparison with other studies and the current problems and deficiencies in this study and describes the limitation and future directions for the measuring the GHG emissions and calculation the emission factors in wastewater treatment plants and incineration facilities. Furthermore, the review of other researches of greenhouse gas emission factors describes the

problems of the emission factors in calculation process. And Chapter 5 outlines the conclusions of the greenhouse gases, the results at the wastewater treatment plant and incineration facilities, the limitations of researches. And the emission factors were calculated by minimizing errors and would be used as basic data for the development of national emission factors in the future.

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Chapter 2. Calculation of emission factors for CH_4 and N_2O from the wastewater treatment facility

2.1 Introduction

Anthropogenic emissions of greenhouse gases (GHGs) have led to a considerable increase in the concentrations of these gases in the atmosphere over the past 100 years (El-Fadel and Massoud, 2001). The United Nations Framework Convention on Climate Change (UNFCCC) is the globally recognized platform for collective action on the reduction of anthropogenic GHG emissions, and the Intergovernmental Panel on Climate Change (IPCC) formulated a guideline in 2006 to account for GHG emissions and mitigate against global climate change in four general sectors (energy; industrial processes; agriculture, forestry, and other types of land use; and waste; Foley et al., 2010; Yoshida et al., 2014). Numerous studies have been conducted on the emissions of methane and nitrous oxide from various sources (e.g., landfills, wetlands, wastewater treatment plants, and sludge treatment plants; Audet et al., 2014; Daelman et al., 2013; Mou et al., 2014; Olsson et al., 2014).

The GHGs carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are emitted from wastewater treatment processes. There is an increasing need to reduce these emissions and to identify the factors controlling the GHG emissions from

wastewater treatment plants (WWTPs; Kampschreur et al., 2009). The direct emission gases are CH_4 and N_2O, whereas CO_2 is calculated from fossil fuel sources, of which biogenic CO_2 is excluded from the calculated values of emissions. The global warming potentials of CH_4 and N_2O are approximately 21 and 310 times that of CO_2, respectively (IPCC, 2007). N_2O can be produced in wastewater processing by nitrifying and denitrifying bacteria under aerobic or anaerobic conditions (Duan et al., 2015; Yan et al., 2014). During nitrification, ammonia is converted into nitrite or nitrate, which is subsequently reduced to dinitrogen gas during denitrification, and both processes can lead to emission of nitrogen oxides (Kampschreur et al., 2009). CH_4 emission from WWTPs occurs mainly from anaerobic decomposition by activating methanogens through surface diffusion and aeration, as well as from the anaerobic digestion of wastewater sludge. CH_4 can be collected and used as an energy source, indirectly reducing CO_2 emissions (Oshita et al., 2014). WWTPs are recognized as one of the sources of GHG emissions (Yan et al., 2014); however, other than research on the anaerobic digestion of sewage sludge (Wang et al., 2011), few studies have been conducted on the generation of CH_4 and N_2O in wastewater treatment.

Greenhouse gases (GHG) are emitted in the processes of removing contaminants from wastewater, primarily from household sewage, which includes a variety of bio-organic pollutants and was treated by physical, chemical, and biological processes to remove these contaminants and produced safe treated

effluent in accordance with standards of effluent wastewater law. By-products of wastewater treatment are usually called sewage sludge that should treat further treatment before disposal to the landfill or incineration process. Wastewater treatment processes are the pretreatment, primary treatment, secondary treatment and tertiary treatment. Pretreatment is the process of removing particles such as cans, sticks and other materials under uniform flow conditions using grit clarifiers. In the primary treatment stage, the first settling basins are used for remove and settle sludge while grease and oils rise to the surface and are skimmed off. Secondary treatment is very important process to eliminate the biological content of wastewater using aerobic biological processes and settle out biological floc. Tertiary treatment is to remove further nutrients such as nitrogen and phosphorus, which can produce the overgrowth of algae after discharging to the environment, e.g. sea, river, wet lands, etc.

Wastewater treatment is generally used to remove the household sewage including commercial sewage, which the ratio of treatment in Table 2.1 was 92.5% in 2014 (MOE, 2015). This was a 7.6% increase for its ratio of treatment and 6.9% increase for treatment capacities from the 2007 level. Sewer penetration rate for Seoul, Pusan, Gwanju, and Daegu city was 100.0%, 99.2%, 98.6%, and 98.3%, respectively, whereas those of Chungnam and Jeonman provinces were 72.7% and 75.1% in 2014. The municipal wastewater treatments were 597 (500 m^3/day or more), which sludge treatments were 95 among them, which recycle use such as

fuel, fertilizer, and so on was 55.7%, incineration method was 22.3%, and landfill method was 18.9%. The facilities for sludge digestion were 62, which reuses of digestion gas were 56.6% for its own use, 16.3% for power generation, 15.0% for sale, and 12.1% for other use.

Seoul city operates four sewage treatments, i.e. Jungryang, Nanji, Tancheon, and Seonam municipal wastewater treatments, which accounts for 20.86% among total facilities (500 m^3/day or more).

Table 2.1. The ratio of wastewater treatment in South Korea (MOE, 2015)

Types	‘07	‘13	‘14
Population (10^3 person)	50,394	52,127	52,419
Treated population (10^3 person)	43,590	48,016	48,506
Treatment facilities[a] (Number)	357 [a] (1,681)[b]	569 (3,205)	597 (3,160)
Ratio of treatment (%)	85.5	92.1	92.5
Capacity of treatment (10^3 ton/day)	23,273	25,330	24,999

[a] Treatment facilities are more than 500 m^3/day.

[b] Treatment facilities are under than 500 m^3/day.

In this study, we used the measured emissions of CH_4 and N_2O derived from the Jungryang sewage plant in Seoul to calculate the emission factors from each basin, including the wastewater sludge anaerobic digestion. These emission factors can be applied to calculate national GHG inventories for wastewater processing. Furthermore, due to the stringent effluent standards in South Korea, the activated-sludge and advanced processes for nutrients have been widely used in large-scale municipal WWTPs. Various studies in South Korea have determined GHG emissions and emission factors for hybrid WWTPs (Kyung et al., 2015) and BNR WWTPs (Lim et al., 2014). However, there have been few studies in WWTPs in South Korea on the emissions and emission factors of each process unit based on the BOD_5 and total nitrogen (TN), including those for the anaerobic digestion tank used for the sludge after settling. Thus, this is a key area requiring additional study to improve the quantification of national GHG emissions. To estimate the emissions, a flux chamber system, which samples gaseous emissions from a defined surface area of the source, was used to measure the concentrations of the fluxes of various gases (Leyris et al., 2005). Furthermore, Jungryang wastewater treatment facility occupied 31.3% among four facilities in Soul city. Greenhouse gas sampling for wastewater treatment plants should actually be conducted in a various plants. However, in this study, there is only one wastewater treatment plant sampled, but it accounts for more than 30% of the total throughput in Seoul. Thus, there is some validity in sampling and emission measurement.

2.2 Materials and Methods

2.2.1 Sampling and methods

The monitoring site was the Jungryang sewage treatment plant, which is one of four wastewater treatment facilities in Seoul, South Korea. The sewage plant treats 1,710,000 m^3/day of domestic wastewater using the activated-sludge and anaerobic/anoxic/aerobic (A^2O) processes, and serves a total population of approximately 3,220,000. The wastewater treated in the WWTP is mostly (approximately 70%) domestic sewage, and the A^2O process is used to remove the high levels of nitrogen and phosphorus. The sludge produced from anaerobic digestion is then dewatered using a belt-filter press. CH_4 gas is collected from the digested sludge tank and used to generate electricity, which fulfils the plant's energy requirements. The average concentrations of influent BOD_5 and TN are 157 mg L^{-1} and 39 mg L^{-1}, respectively. Effluent concentrations are 5.9 mg L^{-1} for BOD_5 and 13 mg L^{-1} for TN, which meet effluent standards: < 10 mg L^{-1} for BOD and < 20 mg L^{-1} for TN. Measurement points and flow diagrams of the WWTP are shown in Fig. 2.1 and the configuration of Jungryang was shown in Table 2.2.

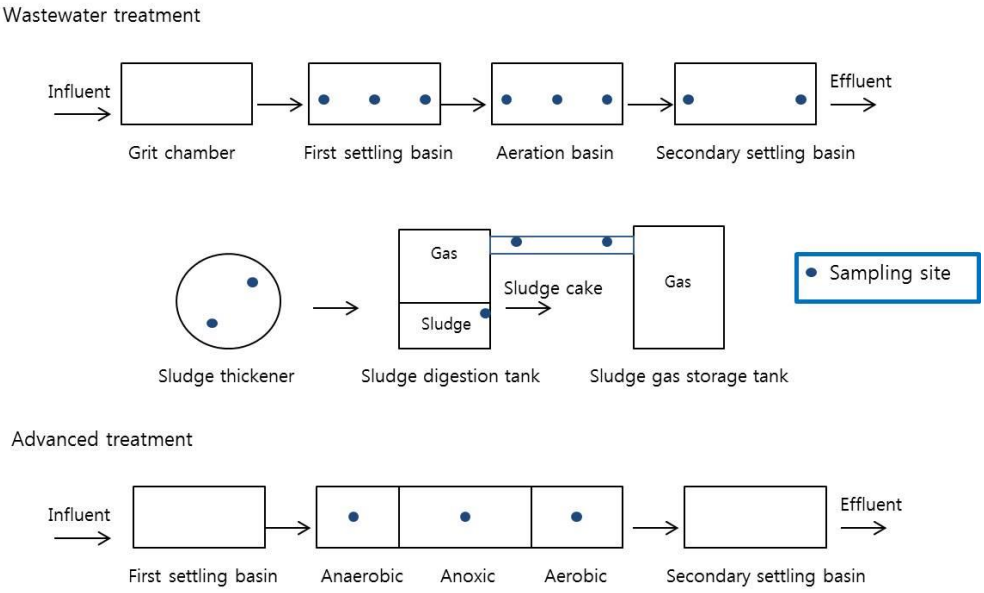

Fig. 2.1. Flow diagram of WWTP and sampling site

Table 2.2. Jungryang wastewater treatment process configuration

Process unit	No. of Process units	Area (m^2)	Inflow of process unit (m^3 d^{-1})
The activated-sludge process			
First settling basin	64	450	759,128
Aeration basin	64	630	754,096
Secondary settling basin	64	526.5	754,096
Sludge thickener	7	452	7,371
The advanced treatment			
Anaerobic reactor	8	292.4	257,300
Anoxic reactor	8	292.4	257,300
Aerobic reactor	8	292.4	257,300
Sludge digestion tank	14	660	6,078 [a]

[a] Inflow quantity of sludge tanks was the sum of all sludge quantity into the sludge tanks.

A variety of flux chamber methods have been used to estimate the fluxes of gases across surface areas (Parker et al., 2013), which include dynamic flux chamber and static flux chamber. Considering the diffusion of gas molecules emitting in soil or water surface, temperature effect, and relative humidity, flux chamber can be used because of accuracy of sample analysis results, sensitivity of sampling on-site, easy controllable technique, and a minimum amount of labor and time. CH_4 and N_2O fluxes were estimated from each processing unit of Jungryang WWTP using a flux chamber system. The first settling basins have closed roofs to prevent the escape of offensive odors, which meet regulations restricting the release of offensive odors. The advanced process tanks are also sealed. And In the primary and secondary sedimentation, the tanks or basins are usually equipped with mechanically driven scrapers that continually drive the collected sludge towards a hopper in the base of the tank where it is pumped to sludge treatment processes. For these reasons, the flux chamber should be portable, non-degradable, and permit ease of sampling. In this study, the flux chamber was modified from a forced-draught chamber and allowed calculations of the concentration difference between the inlet and outlet flows, flow rate, and area covered (Bouwman et al., 2001). The designed flux chamber had a floating bottom area of 0.131 m^2 and an internal volume of 17.73 L; this was equivalent to an internal volume of 15 L floating on the water surface and consisting of a half sphere made of polyvinyl chloride (PVC), and a floating rubber hose on the bottom. The inlet flow of the chamber had four holes on the upper side

of the four directions, and the outlet flow chamber had one hole in the upper center connected to a sampling line (Fig. 2.2), which the silica gel was used to remove moisture and its influence. The chamber was fastened and held in place during sampling to reduce turbulence during floating. Gas bags, previously swept by nitrogen gas and vacuumed, were used to transfer the outlet gases to the laboratory for analysis. On-site sampling was carried out from November 27 until December 7, 2007 (Fig. 2.3). The sludge digestion tank was closed and reused as an energy source through sealed pipe lines. To calculate the emission factors for sludge digestion, measurements of the BOD_5 and TN in the activated sludge and the emitted gases were needed to calculate the emission factors of CH_4 and N_2O, which was impossible with the flux chamber technique.

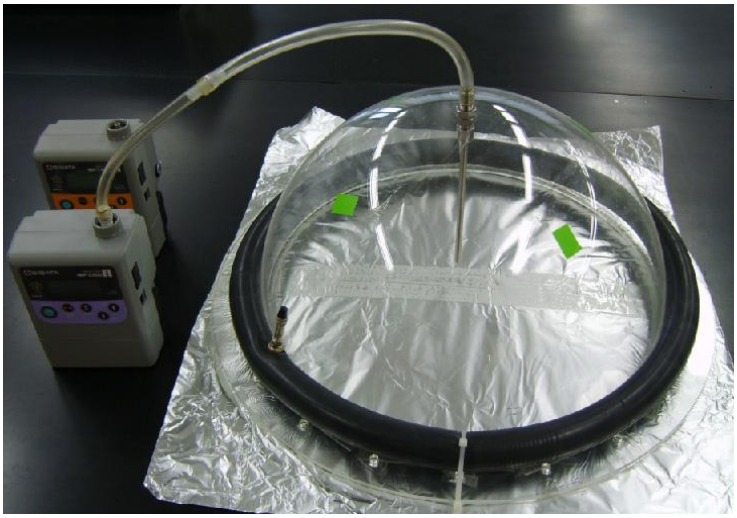

Fig. 2.2. Dynamic flux chamber for wastewater plant

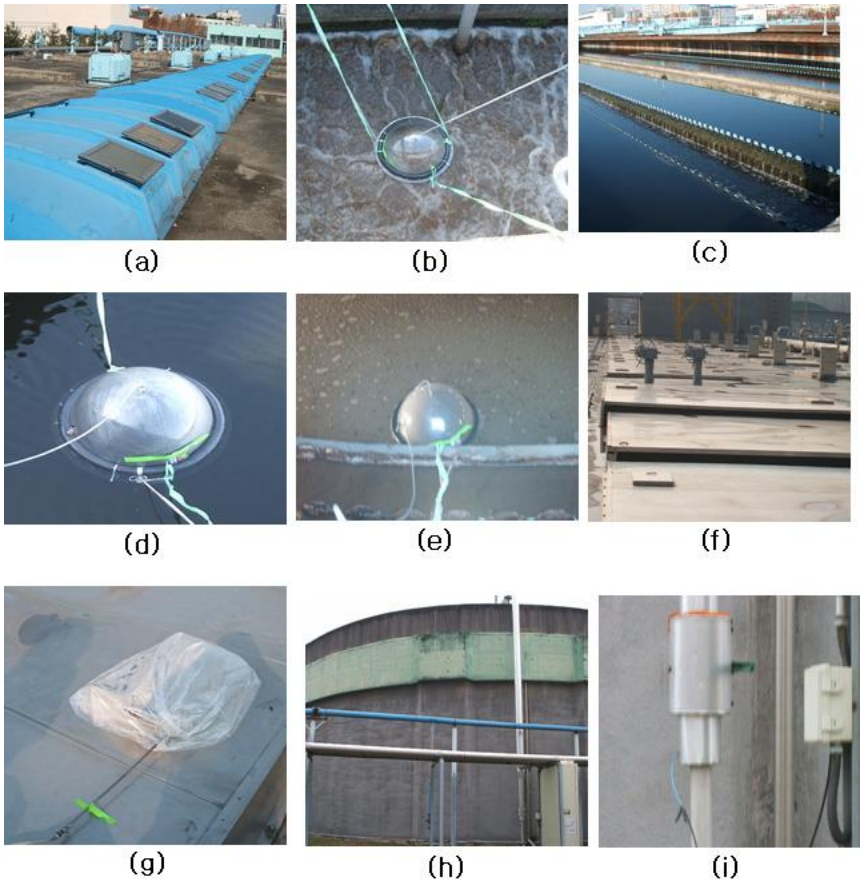

Fig. 2.3. Sampling process in each basin of wastewater treatment plant: (a) first settling basin, (b) aeration basin, (c and d) secondary settling basin, (e) sludge thickener, (f and g) anaerobic/anoxic/aerobic reactor, (h) sludge digestion tank, (i) methane capture device

In addition, to evaluate the problems of quality assurance and quality control of GHG gas monitoring, and if the sample is collected in the Tedlar bag, the GC analysis should be performed within the cut time. In order to overcome this problem, decompression vials were used. In order to evaluate the reproducibility of the GC analysis for N_2O and CH_4 standard gas concentrations, the samples were diluted stepwise and the gas was analyzed. As a result of relative standard deviation (RSD) of retention time and detection area of GC, the reproducibility of the retention time for N_2O was 0.2–0.6% and the overall reproducibility was 0.39% (Table 2.3). And those of CH_4 showed the highest reproducibility of 0.18% at the lowest 0% (Table 2.4), thus, the reproducibility of GC/ECD and FID for the retention time was found to be quite effective. For linearity evaluation of the GC analysis, 70 times for N_2O and 60 times for CH_4 of GC was analyzed. As a result of analysis of correlation on peak area data according to GC injection amount, the linearity of N_2O and CH_4 was found to be more than 0.99.

Table 2.3. The evaluation of GC reproducibility of the retention time for N_2O

Concentration (ppm_v)	# of injection	Mean of peak area	Standard deviation	RSD (%)	Mean of retention time	Standard deviation	RSD (%)
0.65	8	4.8	0.75	15.7	0.758	0.0017	0.2
1.3	8	7.6	0.68	9.0	0.757	0.0019	0.3
4.3	8	19.9	0.66	3.3	0.755	0.0036	0.5
12.4	8	33.2	1.22	3.7	0.755	0.0038	0.5
24.8	8	68.5	0.97	1.4	0.756	0.0032	0.4
30.1	8	94.1	3.64	3.9	0.756	0.0043	0.6
49.6	8	134.2	3.35	2.5	0.757	0.0018	0.2
Average				5.64			0.39

Table 2.4. The evaluation of GC reproducibility of the retention time for CH_4

Concentration (ppm_v)	# of injection	Mean of peak area	Standard deviation	RSD (%)	Mean of retention time	Standard deviation	RSD (%)
2.1	8	1.5	0.09	11.3	1.087	0.0004	0
4.6	8	2.9	0.20	6.9	1.087	0.0016	0.1
9.1	8	6.4	0.40	6.2	1.086	0.0033	0.3
15.6	8	10.7	1.20	6.1	1.085	0.0035	0.3
30.8	8	19.1	1.64	8.6	1.084	0.0036	0.3
45.4	8	29.2	3.02	10.3	1.088	0.0011	0.1
Average				8.2			0.18

2.2.2 Methodologies of emission factors calculation

Prior to on-site sampling, laboratory experiments were performed to estimate how GHG fluxes were influenced by the air flow rate during analysis of the gas bags. CH_4 (1.674%) and N_2O (10.38%) standard gases, provided by the Korean Research Institute of Standards and Science (KRISS), were used and were measured at flow rates of 1, 2, 3, 4, and 5 L min^{-1}. The measured flow rate of the recovered flux was accurate at 5 L min^{-1} (Fig. 2.4). Samples were collected at a constant pumping speed at 3-min intervals.

The Flux, F (mass $area^{-1}$ $time^{-1}$), from the gas samples was calculated at each basin by:

$$F = (C_{outlet} - C_{inlet}) \times \frac{Q}{A} , \qquad (2.1)$$

where C_{outlet} is the concentration of gas in the air flowing out of the chamber, C_{inlet} is the concentration of gas in the air flowing into the chamber, Q (L min^{-1}) is the flow rate through the chamber, and A (m^2) is the area of the bottom of the chamber.

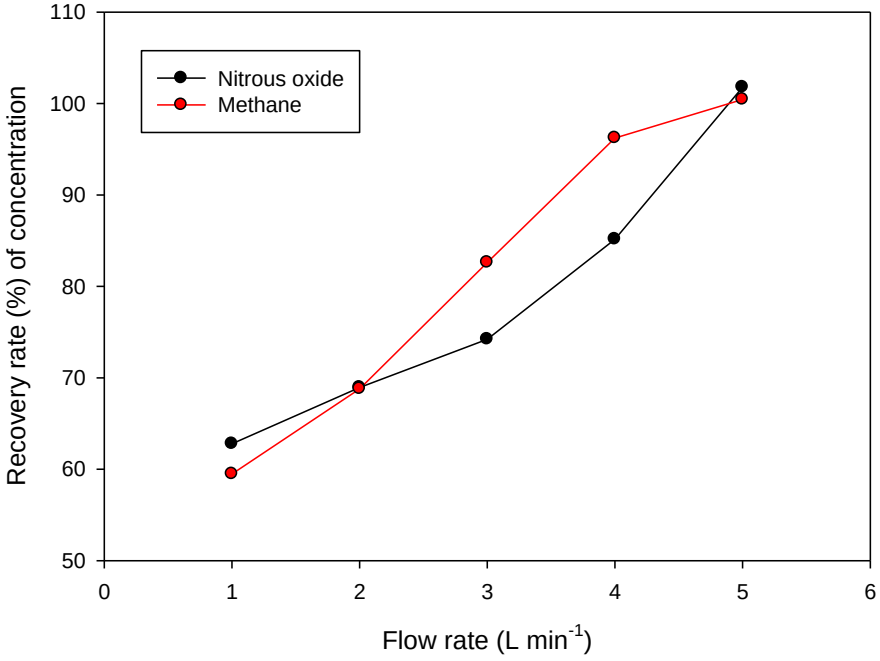

Fig. 2.4. Result of recovery rates for sampling with standard methane gas

The emission factor for Tier 1 is calculated by multiplying the B_o and MCF. However, in this study, the Tier 3 methodology, actually measured CH_4 and N_2O emissions from each basins at the wastewater treatment, is calculated by dividing by activity data (BOD_5). The emission factor formula is as follows:

$$EF = \frac{E}{A} \quad (2.2)$$

Here, EF is the GHG emission factor (g GHG kg- BOD_5/TN^{-1}), E is the GHG emissions from flux by measuring on-site (kg GHG yr^{-1}), and A is the activity level or removed BOD_5/TN of the wastewater treatment plant (mg BOD_5/TN L^{-1}).

2.2.3. Analytical methods

CH_4 concentrations were measured using a Varian CP–3800 gas chromatograph (Varian, Inc.) equipped with a flame ionization detector (FID) and stainless steel packed columns of Porapak Q fused silica columns (2 m length x 28.58 mm diameter); operating conditions for the GC were: 120 ℃ injector temperature, 70 ℃ oven temperature and 320 ℃ detector temperature using a 1.0-mL gas-tight syringe (Hamilton, USA). N_2O concentrations were measured using a Varian CP–3800 gas chromatograph (Varian, Inc.) with an electron capture detector and stainless steel packed columns of Porapak N (2 m length x 28.58 mm diameter); operating conditions for the GC were: 120 ℃ injector temperature, 70 ℃ oven temperature and 200 ℃ detector temperature using a 0.5-mL gas-tight syringe (Hamilton, USA). The carrier gas was ultra-high purity N_2 and flow rate was 30 mL min^{-1}.

2.3. Results and Discussion

2.3.1 Characteristics of each process unit

The observed temperatures in each basin during the sampling period were 15–35 ℃, and the observed air temperatures were 3.2–12 ℃. Measurements of the removed BOD_5 and TN were 96.9–1,771 mg L^{-1} and 12.05–1,550 mg L^{-1}, respectively (Table 2.5).

The first settling basin is used as a pretreatment step in the further treatment of the wastewater. It can remove approximately 30% of the BOD_5 and 35% of the suspended solids and is designed to detain the sewage for 2–3 hours depending on the average rate of sewage flow. The aeration basin is used as a decomposition step and lasts approximately 6 hours. Following the aeration process, the microbe mass is separated in the secondary settling basin for about 3 hours. Sludge thickener is used to thicken the wastewater solids, which are removed in the first and second settling basins, but the value of TN removed was unavailable, and the secondary settling basin TN value was used.

BOD_5 value of the sludge thickener is 12 times higher than that of the secondary settling basin. More BOD is required to decompose the organic compounds considering residence time of the sludge thickeners. The A^2O process is also used for treating wastewater with excessive phosphorus and nitrogen to decrease

eutrophication and improve the water quality. Anaerobic digestion is used to treat sewage sludge containing primary and secondary settling sludge, which produces gases and liquid between fermentations and generates approximately 65,000 ton CH_4/day which is reused to supply energy in the WWTP.

Table 2.5. On-site condition of each process from Jungryang wastewater treatment

Process unit	# of Sampling	Temp. (℃)	Air temp. (℃)	BOD_5/TN_removed (mg L^{-1})
First settling basin	21	15	12	96.9/12.05
Aeration basin	9	18	12.5	103.8/12.09
Secondary settling basin	16	16	12.5	103.8/12.09
Sludge thickener	20	15	3.2	1,244/20[a]
Anaerobic reactor	7	15	8	110.4/16.56
Anoxic reactor	7	15	8	110.4/16.56
Aerobic reactor	7	15	8	110.4/16.56
Sludge digestion tank	7	35	8	1,771/1,550

[a] TN value : Not measured and used organic material value of TN in the secondary settling basin.

In the wastewater treatment, the biological treatment process involves the fermentation of carbon dioxide or other organic compounds with methane gas as the end product when methanogens are produced in anaerobic conditions, and during the denitrification, nitrous oxide can be produced by removing phosphorus and nitrogen. These bacteria are also inactivated due to seasonal effects during the winter, and can be reduced due to the sudden increase in water temperature by dissolved oxygen depletion, and there are also problems in water treatment due to equipment failure of operation and other various reasons. Therefore, the temperature of each process basin that affects microbial growth in wastewater treatment is significant. In this study, the season in which the sampling was performed was winter, but as shown in Table 2.5, the temperature of each basin was kept at 15 ℃ or higher, and it was presented that there was no influence on microbial growth, However, further studies are needed to determine whether other seasonal effects affect greenhouse production.

2.3.2 CH_4 and N_2O fluxes unit processes

Numerous organic compounds and GHGs can be produced under aerobic, anaerobic, and anoxic conditions in WWTPs, with the compounds serving as a growth substance with fermentation and degradation (Metcalf and Eddy et al., 2002.; Wang et al., 2011).

The maximum arithmetic mean of the CH_4 flux generated in the sludge thickener was 1.73 ± 0.08 mg m^{-2} min^{-1}, and the waste activated sludge produced CH_4 under anaerobic conditions, as shown Fig. 2.5, which does not show the sludge digestion tank (Wang et al., 2011). CH_4 emissions occurred during each wastewater treatment process, and the average CH_4 fluxes of the first settling, aeration, and secondary settling basins were 0.46 ± 0.16, 1.16 ± 0.08, and 0.90 ± 0.13 mg m^{-2} min^{-1}, respectively; those of the A^2O reactors were 1.05 ± 0.06, 0.20 ± 0.03, and 0.39 ± 0.05 mg m^{-2} min^{-1}, respectively. In contrast, only small quantities of N_2O were generated in the sludge thickener, and the average flux was $2.60 \times 10^{-3} \pm 1.2 \times 10^{-4}$ mg m^{-2} min^{-1}. The average N_2O fluxes of the first settling, aeration, and secondary settling basins were 0.06 ± 0.005, 0.13 ± 0.002, and 0.02 ± 0.006 mg m^{-2} min^{-1}, respectively, and those of the A^2O reactors were 0.23 ± 0.02, 0.32 ± 0.01, and 0.49 ± 0.01 mg m^{-2} min^{-1}, respectively (Table 2.6). Denitrification is considered the main source of this N_2O, emitting approximately 60% of the total N_2O produced during nitrification in municipal wastewater treatment; however, higher emissions from the

A^2O processes of the advanced treatment activities of nitrification and denitrification bacteria occur in aerated zones than in non-aerated zones (Lim and Kim, 2014). According to the calculated average fluxes of each process, the N_2O fluxes of some basins were relatively low; they were, nevertheless, important for calculating the sum of total emissions and emission factors. Among processes, methane fluxes and emission factors from the sludge thickener have been the highest values except for sludge digestion tank. CH_4 flux from the sludge thickener was also measured up to approximately 3.5 times higher than the secondary settling basin. It was supposed that the anaerobic condition at the bottom of the sludge thickener was dominant, where CH_4 emission is more efficient than that of N_2O due to the anaerobic methane bacteria activities.

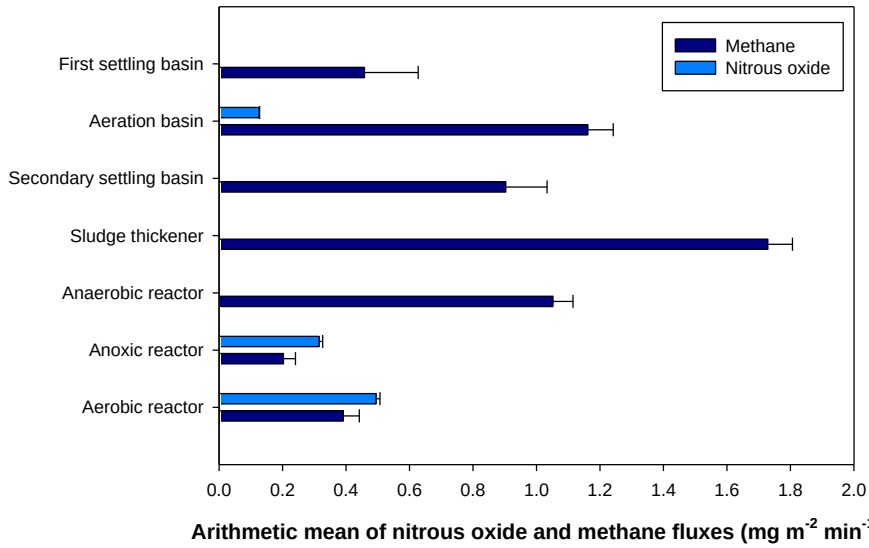

Fig. 2.5. N_2O and CH_4 average fluxes of each wastewater treatment processes.

Table 2.6. Nitrous oxide and methane fluxes range of each basin

Process unit	Flux range (mg m^{-2} min^{-1})	
	N_2O	CH_4
The activated-sludge process		
First settling basin	0.04-0.07	0.19-0.73
Aeration basin	0.12-0.13	1.06-1.29
Secondary settling basin	$9.75x10^{-3}$-0.04	$5.11x10^{-3}$-1.97
Sludge thickener	$2.63x10^{-3}$-$5.61x10^{-3}$	0.13-6.82
The advanced treatment		
Anaerobic reactor	0.19-0.27	0.96-1.13
Anoxic reactor	0.29-0.33	0.16-0.26
Aerobic reactor	0.47-0.51	0.28-0.44
Sludge digestion tank [a]	0.52-2.21	$5.20x10^{4}$-$7.19x10^{4}$

[a] Sludge digestion tank : Not available of the flux measurement and concentration (ppm_v) of the sludge gas in the digestion tank.

2.3.3. Measurements from sludge digestion tank

The anaerobic digestion process treats organic wastes such as sewage sludge, food waste, and livestock manure using microorganisms, which not only can effectively reduce the amount of waste but can also be used as a by-product and get biogas of carbon dioxide and methane. Anaerobic digestion is a process that decomposes organic matter under oxygen-free conditions to produce methane (60–70%), carbon dioxide (30–40%), water vapor, nitrogen compounds, hydrogen sulfide, ammonia, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the anaerobic digester, various parameters for process such as pH, alkalinity, temperature, and residence time affect the speed of microorganisms and efficiency of basin. The optimal pH for hydrolysis is 5.2–6.3 and the optimum pH of the methane-forming microorganism is 7.0–7.5, which is known to be significantly more sensitive to changes in pH than microorganisms involved in other stages (Namkung and Jeon, 2010). Additionally, the anaerobic digestion process is generally performed at a high temperature (45–58 ℃), middle temperature (30–38 ℃), and low temperature (20 ℃ or less), and should be kept constant temperature. For complete digestion, the solid retention time should be at least 5 days, and if is less than 5 days, the concentration of volatile fatty acids will increase due to the washout of the methanogenic microorganisms. Generally, the mesophilic digestion is about 30 days, and it is about 12 days in the case of high temperature digestion. Although anaerobic

digesters are classified by country and according to the type of waste, they can be classified into 1-stage digester and 2-stage digester depending on the construction of the digestion tank, and middle temperature digestion and high temperature digestion according to the operation temperature. In addition, depending on the solid concentration, it can be classified into wet digestion and dry digestion, also batch digestion and continuous digestion depending on the operation mode.

In the Jungryang wastewater treatment, the temperature of the digestion tank was maintained at approximately 35 ℃ and CH_4 is produced by sludge digestion process, which the digesters have middle temperature operation condition and 30 days for average retention time. The percentage of CH_4 was approximately 64% of the total gas in the sludge digestion tank, which was mostly reused for on-site electricity generation. The average concentrations of CH_4 and N_2O in the sludge tank were 66,420 parts per million (ppm_v) and 1,078 parts per billion (ppb_v), respectively. N_2O is generated in small quantities by methanogens during the digestion period in the absence of oxygen, which converts these products to CH_4 and CO_2. It was not possible to measure fluxes using the chamber technique for direct sampling in the sludge digestion tank. To determine the emission factors and emissions, it was therefore necessary to estimate the concentrations in the sludge biogas and measure the digestion sludge in the tank.

CH_4 and N_2O emissions in the sewage treatment facilities are calculated by BOD basis of input activities during the microbial treatment of wastewater. The anaerobic

digestion tank for sludge treatment is a reactor for treating sludge by anaerobic bacteria under anaerobic conditions, which is inconsistent with the BOD basis for oxygen demand bacteria. Therefore, it is necessary to further study the emission calculation formula in the sewage treatment facilities in the future.

2.3.4. CH_4 and N_2O emissions and emission factors from Jungryang WWTP

The emission factors from each process unit were calculated from the measured concentrations of CH_4 and N_2O, as well as from those of the removed BOD_5 and TN, which are represented in Table 2.7. The total N_2O and CH_4 emission factors from the activated-sludge process were 1.256 ± 0.5 g N_2O/kg TN and 3.734 ± 1.21 g CH_4/kg BOD_5, respectively. The total N_2O and CH_4 emission factors from the advanced treatment were 1.605 ± 0.15 g N_2O/kg TN and 4.022 ± 0.12 g CH_4/kg BOD_5, respectively. The N_2O and CH_4 fluxes from the sludge digestion tank were 0.012 ± 0.01 g N_2O/kg TN and 227.0 ± 23.53 g CH_4/kg BOD_5, respectively. At this WWTP, the arithmetic mean of CH_4 emission factors were generally higher than those of N_2O, and emissions were dominantly affected by more the methanogenic bacteria than the nitrification-denitrification bacteria, which requires further study. Yan et al. (2014) calculated an emission factor of 0.8 g N_2O/ kg TN for the A^2O treatment of nitrous oxide, which was similar to our value. Their CH_4 emission factor was 0.9 g CH_4/ kg chemical oxygen demand (COD), calculated using the organic analytic method of COD, which is differed from our value of BOD. Kyung et al. (2015) calculated emission factors for CH_4 and N_2O of 0.19 kg CH_4/ kg BOD_5 and 0.66 kg N_2O/ kg TN, respectively, for five-stage Bardenpho processes using laboratory batch reactor analysis. The differences in the values of the emission factors are mostly due

to the different capacities and types of operations and conditions. In addition, the different measurement methods also produced differences in the estimated values (e.g., the chamber technique used a small surface compared with the wastewater method). Thus, it is important to consider the operational systems and measurement methods, including the operating time, capacities of the facilities, and conditions of the organic compounds, for wastewater treatment processes and to find the most appropriate measurement method for the specific WWTP studied. Therefore, more measurements are necessary to provide quantitative GHG emission data for various WWTPs.

Table 2.7. Emission factors of wastewater treatment processes

Process unit	Emission factor	
	N_2O (g N_2O/kg TN)	CH_4 (g CH_4/kg BOD_5)
The activated-sludge process		
First settling basin	0.263 ± 0.03	0.258 ± 0.09
Aeration basin	0.672 ± 0.37	0.720 ± 0.63
Secondary settling basin	0.226 ± 0.01	0.670 ± 0.31
Sludge thickener	0.195 ± 0.09	2.086 ± 0.18
Total	1.256 ± 0.50	3.734 ± 1.21
The advanced treatment		
Anaerobic reactor	0.182 ± 0.02	0.125 ± 0.01
Anoxic reactor	0.249 ± 0.01	0.024 ± 0.004
Aerobic reactor	1.174 ± 0.03	0.139 ± 0.02
Total	1.605 ± 0.15	4.022 ± 0.124
Sludge digestion tank	0.012 ± 0.01	227.0 ± 23.53

The emissions from Jungryang sewage treatment plant from 2006 to 2014 were estimated by applying the emission factors in Table 2.7. GHG emissions from the sludge digestion tank were excluded because no data were available on the treated BOD and TN concentrations (MOE, 2007–2015). The throughput of the biological treatment basins were high, resulting in greater emissions than the advanced treatment basins. For CO_2 equivalent emissions, N_2O emissions are significant portion to total emissions because GWP of N_2O is greater than that of CH_4 (Table 2.8). Therefore, it is necessary to estimate emission factors for plant-specific and country-specific.

Table 2.8. Emissions of Jungryang wastewater treatment

Year	Activated treatment	Advanced treatment	CH_4 emission			N_2O emission			Total emission (tCO_2-eq/yr)
			Activated	Advanced	Total	Activated	Advanced	Total	
	(m^3/day)	(m^3/day)	ton CH_4/yr		tCO_2-eq/yr	ton N_2O yr^{-1}		tCO_2-eq/yr	
2006	1,083,335	259,324	207	53	5,444	16	3	5,922	11,366
2007	1,119,944	307,729	214	62	5,797	16	4	6,288	12,084
2008	1,056,228	268,082	202	54	5,373	15	4	5,837	11,210
2009	1,048,200	244,800	200	50	5,242	15	3	5,704	10,946
2010	1,112,421	246,791	212	50	5,507	16	3	5,999	11,507
2011	1,049,371	248,202	200	50	5,261	15	3	5,724	10,984
2012	1,091,694	252,644	208	51	5,449	16	3	5,931	11,381
2013	1,086,661	240,591	207	49	5,378	16	3	5,859	11,236
2014	1,055,916	219,040	201	44	5,163	15	3	5,631	10,794

2.4 Conclusions

The characteristics of the CH_4 and N_2O emissions were analyzed in the Jungryang WWTP, South Korea. The sludge thickener produced the highest CH_4 emissions, and the aeration basin had the highest N_2O emissions, excluding the sludge digestion tank. The N_2O emission factor of the sludge digestion tank was lower than that of CH_4, which is used as recyclable energy and deducted from total GHG emissions. Each emission factor for processing units is significant for calculating total emissions.

In addition, in this study, CH_4 and N_2O emissions were measured by each basin and those of emission factors were calculated by emissions from each flux for basins and removed BOD_5/TN from wastewater treatment. Although sampling was conducted in one place, it is to be meaningful because it occupies 6% of the total municipal wastewater treatment plants in Korea. However, additional studies for seasonal changes such as spring and summer are needed. In addition, in order to calculate national emission factors, a variety of wastewater treatment plants should also be performed and it is necessary to study according to wastewater treatment methods, seasonal changes, and other operational conditions.

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Chapter 3. Calculation of emission factors for CO_2, CH_4 and N_2O from waste incineration facility

3.1 Introduction

A large amount of waste is being generated due to economic development, population growth, and increased consumption. Waste incineration as a waste disposal method is increasing in popularity worldwide due to the lack of land and the potential for soil and water pollution associated with landfilling, as well as the added benefit of the potential for energy recovery from incineration (Harris et al., 2015).

Greenhouse gases (GHGs) emitted from waste incineration processes include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), with emissions of CO_2 being more significant than those of CH_4 and N_2O (IPCC, 2006). The production of household and industrial waste in Korea totaled 48,000 and 96,000 tons per day in 1995, respectively. By 2012, the production of household and industrial waste had increased to 49,000 and 146,000 tons per day, respectively, that is, an increase of approximately 1.5 times for industrial waste (GGIRCK, 2014). In addition, emissions from the waste sector were 14.8 million tons of CO_2 equivalent (CO_2 eq) in 2012, accounting for 2.2% of the total emissions in South Korea. This

was a 49.4% increase from the 1990 level and a 1.6% increase from the 2011 level (GGIRCK, 2014). In 2014, waste generation was approximately 388,000 tons per day and the recycling rate was 84.8%, which represented a 0.9% increase from the 2013 level (landfill: 9.1%, incineration: 5.8%, other: 0.3%) (MOE, 2015). In contrast, in Europe, approximately 22% of waste is currently incinerated. This amount is increasing due to the EU Landfill Directive (Harris et al., 2015), and GHG emissions from the waste sector emission now account for 152 million tons CO_2 eq, which represents a 37.7% decrease from the 1990 level (EEA, 2015).

Previous studies have reported various values for GHG emissions and emission factors that are specific to certain countries, waste type, and waste management practices. Astrup et al. (2009) measured direct emissions from a combustion plant as well as indirect upstream contributions. The content of fossil carbon in the input waste was found to be around 40% of the direct fossil carbon-related emissions. It was reported that the separate collection of municipal waste as a management practice affected GHG emissions (Calabrò, 2009), with fossil carbon emission factors ranging from 27 to 40 kg CO_2/GJ for residual household waste incineration (Larsen and Astrup, 2011). Also, a life cycle assessment (LCA) of a selective non-catalytic reduction (SNCR) NO_x-cleaning system, operating with an ammonia slip (i.e., loss of ammonia) demonstrated an effect on GHG emissions (Møller et al., 2011). Direct and indirect emissions of CO_2-eq and NOx were examined for a district heating system using LCA principles and were compared to a hypothetical

scenario where the most likely alternative waste treatment and heat supply technologies were used (Brattebø et al., 2012). Annual mean fossil carbon emissions from five Swiss incinerators were calculated using the radiocarbon (^{14}C) method, and were found to be between 43.4 ± 3.9 and 54.5 ± 3.1%, with the variations explained by the waste composition of the respective plants (Mohn et al., 2012). Recently, both N_2O and CH_4 emissions and emission factors were examined at five Swiss waste incineration facilities burning a mixture of household and industrial waste with grate firing (Harris et al., 2015). For the removal of NO_x, two of the plants used selective non-catalytic reduction (SNCR), while three plants used selective catalytic reduction (SCR). It was found that N_2O emissions from incineration plants with SCR were ten times lower than from plants with SCR (Harris et al., 2015)..

In Korea, CO_2 emissions from different waste incineration type, namely, municipal, industrial, construction, and hazardous waste between 1998 and 2005 were determined by applying the annual mean carbon contents reported in the national waste survey (Jang et al., 2008). There were several reported studies which reported GHG emission using measured data from incineration plants (Kan et al., 2008; Kim et al., 2010; Park et al., 2011). Emissions of CO_2 and N_2O were examined at six incineration plants treating different waste streams, that is, municipal, industrial (with sludge), construction, and specified waste (with sludge) by analyzing the flue gas (Kan et al., 2008; Kim et al., 2010). Park et al. (2011) also

examined N_2O emissions and emission factors from three municipal solid waste (MSW) incinerators in Korea treating with either a stoker type or both the stoker and rotary kiln types for NO_x removal. The emission factors from the three different plants were calculated as 71, 75, and 153 g-N_2O/ton-waste, respectively. All these studies have suggested that GHG emissions and emission factors vary according to the type of waste incineration, plant operation (e.g., NO_x removal types), and local waste management practices, thus more comprehensive data is required to calculate the national GHG emission factors from waste incineration facilities in Korea using the 'bottom-up' measurement of plant-specific GHGs. However, the data obtained from their studies are not yet sufficient to produce GHG emission factors in national level in Korea. In this study, we estimated the emission factors by measuring GHG such as CO_2, CH_4, and N_2O from the flue gases at nine selected waste incineration plants which cover different operation systems (i.e., stoker, fluidized bed, moving grate, rotary kiln, and kiln & stoker), different nitrogen oxide (NO_x) removal systems (i.e., selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR)), and different waste types such as municipal solid waste (MSW), commercial solid waste (CSW), and specified waste (SW), respectively. The effects of the waste types, NO_x removal methods, and combustion temperatures in the incineration plants, on the GHG emission factors were examined in details. The results obtained in this study were used to comprehensively provide national GHG emission factors in each type of incineration facilities in Korea.

3.2 Materials and Methods

3.2.1 Waste information and sample collection

In Korea, waste comprises municipal waste (e.g., solid and food waste from households, industrial processes, and commercial activities), treatment waste (e.g., sludge and residues from municipal, industrial, and human or livestock waste treatment facilities), construction waste, specified or designated waste (e.g., acids and alkalis, oil, organic solvents, synthetic polymers, fly ash sludge from industrial sites, which contains hazardous ingredients and needs safe management), and medical waste (MOE 2008, 2015). Between 2007 and 2014, the total amount of waste generated in Korea steadily increased by 27% (i.e., approximately 3.8 million tons in 2007 to 5.2 million tons in 2014), compared to population growth of 4% (MOE, 2008, 2015). Over the same period, the generation of treatment, construction, specified, and medical waste increased by 25, 7, 27, and 52%, respectively, while the generation of municipal waste slightly decreased by 1%. Furthermore, in this period, the total amount of waste treated by landfill, incineration, and recycling increased by 15, 24 and 30%, respectively, indicating that recycling rates are gradually rising and the use of "Waste to Energy" (WTE) plants is also increasing (MOE, 2008, 2015).

As shown in Table 3.1, the total number of MSW incineration facilities in

Korea is 180 in 2007, with the waste treating capacity of A and B facility is 12,500 kg/hr and 8,333 kg/hr, respectively. There were a total of 1,016 CSW incineration facilities in workplace of the self-processing companies in 2007, and the capacity of the C facility was 5,834 kg/hr (MOE, 2008). In addition, the total number of facilities handling specified waste (SW) (waste oil, other organic solvents, waste acid, waste alkali, and waste synthetic resin, etc.) amounted to approximately 180 in 2007 (MOE, 2008). Therefore, it is considered that the selected facilities for sampling in this study can represent various incineration facilities in Korea.

Table 3.1. Classification by facility capacity.

Facility capacity(kg/hr)	# of MSW Incineration facility[a]	# of CSW incineration facility[b]	# of specified waste incinerator[c]	Selected facilities in this study
≥10,000	19	4		A
5,000≤ and <10,000	14	7		B, and C
<5,000	147	1,005		
≥4			21	E (3)[d], and I (2)
2≤ and <4			87	D (1), F (1), and H (1)
<2			72	F (1), G (2), and H (1)
Total	180	1,016	180	

[a] Municipal solid waste facilities operated by local authorities based on 2007 (MOE, 2008).

[b] Commercial solid waste facilities operated by self-processing based on 2007 (MOE, 2008)

[c] Specified waste incinerators operated by approximately 120 self-processing facilities and the treated materials were waste oil, organic solvents, waste acid, waste alkaline, and waste synthetic resin.

[d] Number of incinerators.

Table 3.2 shows the characteristic details of nine selected waste incineration plants in Korea, in terms of their operation types, NO_x removal technologies, and other information related to the estimation of GHG emissions. Flue gas samples were collected from these plants between August 2005 and August 2007. Plants A and B were operated by local authorities to incinerate MSW and were continuous stoker types. For NO_x removal, facility A had an SCR system, while facility B had an SNCR system. Plant C was operated privately to treat solid waste with continuous fluidized bed combustion technology and an SCR system to treat the off-gas. Plants D to I were operated continuously with SNCR systems, to treat specified or designated waste. A kiln & stoker or a stoker-only was used in these plants except that the plant F additionally had a moving grate and plant G had a rotary kiln.

Table 3.2. Details of the waste incineration plants investigated in this study

Plant	Type of plant	De-NO_x system	Stack Temp. (℃)	# of samples	Capacity (ton day^{-1})	Flow rate (m^3 h^{-1})	Incineration (ton day^{-1})
Municipal solid waste (MSW)							
A	Stoker	SCR	190	53	200	21,850	79
B	Stoker	SNCR	171	25	300	61,036	210
Commercial solid waste (CSW)							
C	Fluidized	SCR	207	5	48	19,000	54.0
Specified waste							
D	Kiln & stoker	SNCR	167	10	161	39,750	80.34
E	Stoker	SNCR	169	15	288	50,167	200.0
F	Kiln & stoker	SNCR	165	5	75	42,000	74.84
	Moving grate	SNCR	200	5	44	43,200	43.92
G	Stoker	SNCR	165	10	58	37,300	54.0
	Rotary kiln	SNCR	165	5	31	38,000	27.0
H	Kiln & stoker	SNCR	168	5	60	53,000	60.0
	Stoker	SNCR	168	5	36	28,000	36.0
I	Kiln & stoker	SNCR	168	5	96	45,000	49.51
	Stoker	SNCR	169	5	96	50,000	49.51

*SCR: selective catalytic reduction, SCNR: selective non-catalytic reduction

* Data for plants C to I are obtained from Choi et al. (2007).

The flue gas was collected and analyzed to estimate GHG emissions based on the US EPA method (US EPA, 2009). In brief, a constant flow of flue gas was extracted from the duct with a sampling probe connected to a cooling device, which kept performing at a constant flow rate using a portable vacuum pump (SIBTA ∑100, Sibata Scientific Technology LTD., Japan). The flue gas was discharged to the atmosphere from the duct at a rate of more than 10 m/sec and with a temperature over 160 ℃. Owing to the high temperature, the sample probe was made from stainless steel and had a length of around 1.5 m. The sampled gas was collected in Tedlar bags (SKC Ltd., Eighty Four, PA, USA) for the later analysis of GHGs. Additionally, a water cooling device for protecting the sample bags from the high temperature and a silica gel were used to eliminate the influence of water vapor (Wight, 1994; Park, 2011; Choi, 2007). Prior to sampling, water absorbing materials were tested for silica gel. The CO_2 concentration range of silica gel was 7.8–9.6% (Table 3.3), which silica gel was used as an absorbent in this study. In addition, to evaluate the problems of quality assurance and quality control of GHG gas monitoring, the photoreaction was evaluated by exposure to sunlight using 3% CO_2 standard gas. The average area value of the GC graph before light exposure was 116.3 and the average value after one day was 115.8. Therefore, it was estimated that the effect of CO_2 gas on the reaction for light exposure was scarcely affected.

Table 3.3. CO_2 analysis of GC-TCD using silica gel

Stack	# of analysis	Injected frequency area			Mean of % conc.	Std. Dev.	% RSD
		1	2	3			
1	1	559.6	550.6	530.7	9.0	14.8	2.7
	2	521.5	524.6	530.9	8.6	4.8	0.9
	3	585.4	572.8	577.5	9.5	6.4	1.1
	4	545.2	558.9	554.9	9.1	7.0	1.3
	5	476.5	542.8	557.3	9.1	8.4	1.5
	6	504.7	466.7	488.1	7.9	10.7	2.2
2	7	506.1	514.4	516.0	8.4	6.1	1.2
	8	506.1	498.6	508.8	8.3	5.3	1.0
	9	487.6	483.9	498.1	8.1	7.4	1.5
	10	494.3	498.0	491.4	8.1	3.3	0.7
	11	467.9	475.6	470.7	7.8	3.9	0.8
	12	493.5	493.0	494.4	8.1	0.7	0.1

3.2.2 GHG analysis

The CO_2 concentrations from incineration facilities treating municipal solid waste (MSW) were measured by a gas chromatograph (GC), with a thermal conductivity detector (TCD) (HP 6890; Agilent, Santa Clara, CA) using an "HP-Plot Q" column (Agilent), namely, a 30 m fused silica capillary column, with 0.53 mm inner diameter and 40 μm film thickness. The temperatures of the injection port, oven, and detector for GC-TCD were 250, 60, and 280 ℃, respectively. The carrier gas was ultra-high-purity helium, with injections made using a 50 μl gas tight syringe (Hamilton, Reno, NV, USA). Carbon dioxide standards of 3.03, 9.99, and 17.95% were used for calibration, with a strong correlation obtained ($r^2 = 0.9991$).

The analytical methods used to determine CH_4 and N_2O concentrations in the samples are described by Hwang et al. (2016). Gas samples for CH_4 were analyzed using a Varian CP-3800 GC (Varian Inc., Palo Alto, CA, USA) equipped with a flame ionization detector (FID) and stainless steel packed columns of Porapak Q fused silica columns (2 m length and 28.58 mm diameter). The temperatures of the injector, oven, and detector were 120, 70, and 320 ℃, respectively, with injections made using a 1.0 mL gas-tight syringe (Hamilton Co., Reno, NV, USA). The N_2O concentrations were analyzed using a Varian CP-3800 GC (Varian Inc., Palo Alto, CA, USA) with an electron capture detector and stainless steel packed columns of Porapak N (2 m length and 28.58 mm diameter). The temperatures of the injector,

oven, and detector were 120, 70, and 200 ℃, respectively, with injections made using a 0.5-mL gas-tight syringe (Hamilton). Ultra-high-purity nitrogen was used as the carrier gas, with a flow rate of 30 mL min^{-1}.

In addition, the CO_2 concentrations from commercial solid waste (CSW) and specified waste (SW) facilities were measured from the transportation management system (TMS) real time data installed in the facilities (D, F, H (stoker), and I facilities). However, C, E, G, and H (Kiln & stoker) facilities had not installed TMS system, thus there were no CO_2 data available.

3.2.3 Calculation of GHG emissions and emission factors

The calculation of GHG emissions and emission factors requires multi-step data, such as the concentrations of GHGs, values of the flow rate, and the activity level of the incineration plant (US EPA, 2006; IPCC, 2006). Emissions of CH_4 and N_2O were calculated from the GHG concentrations and the flow rate of the duct, while the emission factors were calculated by dividing the GHG emissions by the activity level of the incineration plant, as shown in details by Park et al. (2011).

$$E = \sum_i (EC_i \times FGR_i) \times conversion\ factor \quad (3.1)$$

Here, E is the GHG emissions (ton GHG yr^{-1}), EC_i is the concentration of a measured GHG (ppm_v, or μg m^{-3}), and FGR_i is the flue gas flow rate through the duct (m^3 h^{-1}), conversion factor (ppm_v, or μg GHG m^{-3} into ton GHG/yr), and i is greenhouse gas such as CO_2, CH_4, and N_2O.

$$EF = \frac{E}{A} \quad (3.2)$$

Here, EF is the GHG emission factor (kg GHG ton-$waste^{-1}$), E is the GHG emissions (ton GHG yr^{-1}), and A is the activity level of the incineration plant (ton

waste yr^{-1}).

Biogenic emissions from the municipal solid waste incineration should be excluded to obtain the CO_2 emissions, which are calculated by multiplying the factors with a fossil fuel origin, namely, the waste fraction (WF), the dry matter content (dm), the carbon fraction (CF), the fossil carbon fraction (FCF), and the oxidation factor (OF) given in Chapter 1.3 (IPCC, 2006).

$$CO_2\ fossil\ fuel\ factor = \sum_j (dm_j \times CF_j \times FCF_j \times OF_j) \quad (3.3)$$

Here, CO_2 fossil fuel factor is value from fossil fuel combustion (fraction), which A facility is 0.1298 and B facility is 0.1009, and dm_j is dry matter content in the waste (wet weight) incinerated (fraction), CF_j is fraction of carbon in the dry matter (total carbon content) (fraction), FCF_j is fraction of fossil carbon in the total carbon (fraction), OF_j is oxidation factor (fraction), which is assumed that 100% oxidized (1.0), j is component of the MSW incinerated such as food, paper/disposable nappies, wood, textiles, vinyl/rubber, plastics, and inert waste.

$$CO_2\ Emissions\ for\ MSW = (EC_i \times FGR_i \times CO_2\ fossil\ fuel\ factor) \times conversion\ factor \quad (3.4)$$

Here, CO_2 Emissions for MSW is CO_2 emissions from fossil fuel combustion (ton GHG yr^{-1}), EC_i is the concentration of a measured GHG (ppm_v, or $\mu g\ m^{-3}$), and

FGR_i is the flue gas flow rate through the duct ($m^3\ h^{-1}$), conversion factor (ppm_v, or μg GHG m^{-3} into ton GHG/yr), and i is greenhouse gas such as CO_2, CH_4, and N_2O.

Plant-specific data (Tier 3 and Tier 2a) obtained from each incineration plant were used to obtain WF, dm, and CF, while default values (Tier 1) of the FCF and the OF were obtained from the IPCC (2006). In addition, for MSW, the IPCC Tier 3 method for plant- specific emission factors can be used when the factors affecting both the FCF and the OF were extracted from plant-specific data.

3.2.4 Statistical analysis

A Monte Carlo simulation was applied to analyze sensitivity of GHG emission factors in MSW. A facility was able to perform statistical analysis with 53 samples and B facility had 25 samples available. But C–I facilities were excluded from statistical analysis due to small sampling of 10 or less.

In order to find the probability distribution, a Monte Carlo simulation was performed 100,000 iterations ($p < 0.05$) using input data (e.g. flow rate, incineration, and GHG concentration). The most proper probability distributions for GHG concentrations that had the largest effect on the results were as follows: The probability distributions for CO_2, CH_4, and N_2O at A facility were logistic, gamma, and log normal distributions, while those of at B facility were normal, log normal, and logistic distributions (Fig. 3.1).

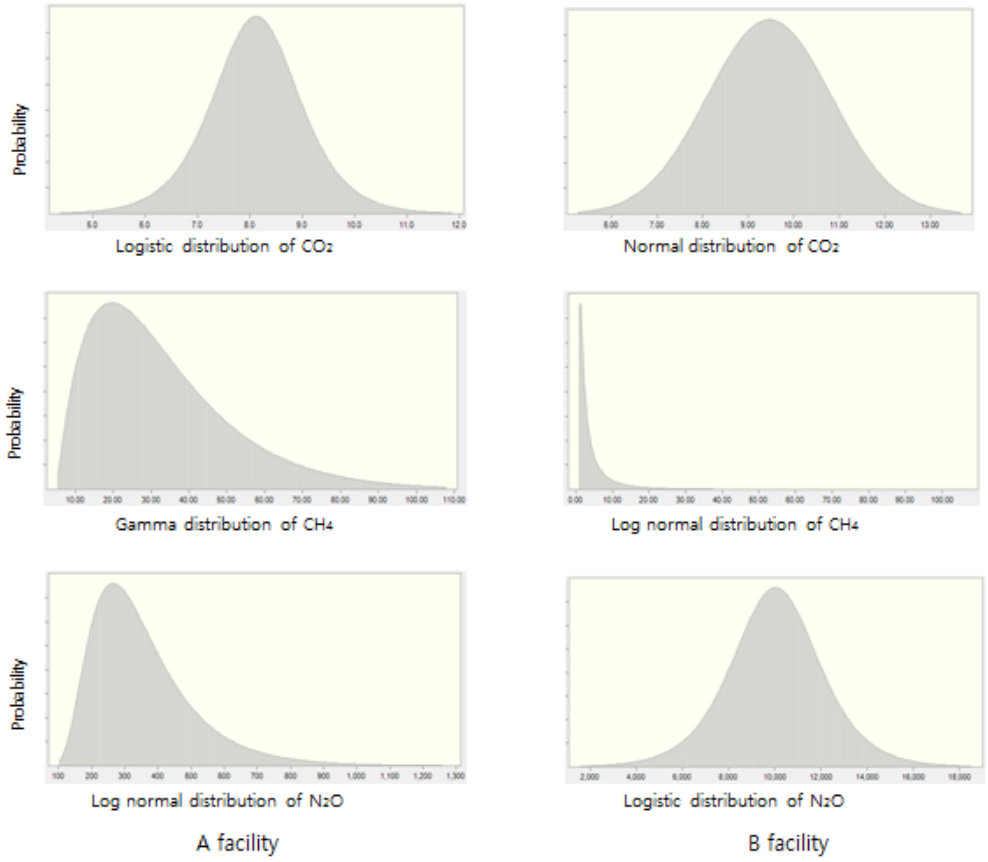

Fig. 3.1 Probability distributions for GHG concentrations in MSW.

3.3 Results

3.3.1 GHG emissions from MSW

Plants A and B were managed by the same local authority, and the components of these two facilities were very similar because they treated municipal waste discharged from similar homes and commercial locations. To calculate CO_2 emissions from plants A and B, the waste streams were classified as follows: food waste, paper (including diapers, which were otherwise difficult to classify), wood, textiles, vinyl/rubber, plastic, and others (inert waste). In the 2006 IPCC default values (see Appendix), paper and diapers/nappies are categorized seperately, and the carbon content and fossil content of paper and diapers of 2006 IPCC default was 46%, 1%, and 60%, 10%, respectively. The carbon content of paper containing diapers in this study was 51%, and those of IPCC default of average for paper and nappy was 53%, which the carbon content was similar in this study and IPCC default. But the fossil carbon contents of paper and nappy for IPCC default were different, which the values might have an effect for total CO_2 emissions.

As shown in Table 3.4, food waste, paper, and plastics comprised the majority of the waste. The remaining types of waste accounted for one-third of the total. The dm and CF of all waste streams except inert waste were surveyed at plant B, which was surveyed six times, but not at plant A. For the dm, plastic, vinyl, and rubber

were all included, and the final value was the highest (76.5%) of all of the waste streams. For wood waste, it was 75.2%, followed by textiles (70.2%), paper (58.5%), and food waste (55.0%). For the CF, plastic waste (including vinyl and rubber) was determined to have the highest value (76.5%), followed by paper (50.7%), textiles (48.2%), wood (48.2%), and food (43.6%). The values of dm and CF from plant B were then applied at plant A because both facilities received similar heterogeneous mixtures of waste. Values for the FCF and factors for inert waste were obtained from IPCC (2006) data and the OF was assumed to be 100%.

In the estimation of CO_2 emissions, the difference in the 2006 IPCC guidelines calculation method compared to GPG 2000 (GPG, 2000) added dry matter content and oxidation factor instead of the burn out efficiency of combustion. And even if the fuel contains moisture/water, and if the incineration combustion efficiency is high, it does not have a great influence on the CO_2 emissions (compared with equation 1.10 and 1.11). Furthermore, efficiency of combustion in GPG 2000 for MSW is 95% default value and the range is 95–99% (see Appendix). The efficiency of combustion of A (Uijeongbu city) and B (Goyang city) facilities was more than 99%, and it did not seem to be affected much by the dry matter content (dm) (Uijeongbu, 2008 and Goyang, 2008). But as mentioned above, CO_2 emissions could affect the emission factors according to fossil carbon content, and the values of fossil carbon content for paper and nappy were 1% and 10%, respectively, which were not large and might not significantly affect total emissions.

Table 3.4. The waste fraction (WF), dry matter (dm) content, carbon fraction (CF), and fossil carbon fraction (FCF).

Composition of MSW	Waste fraction (%)		Dry matter content in % of wet weight		Carbon fraction in % of dry matter		Fossil carbon fraction (%)
	A	B	This study	Default[b]	This study	Default[b]	Default[b]
Food	20.0	26.6	54.98	40	43.60	38	0
Paper	32.0	36.9	58.51	90	50.70	46	1
Wood	9.2	4.3	75.18	85	48.15	50	0
Textiles	3.2	6.5	70.15	80	48.20	50	20
Vinyl/rubber	9.1	6.9	76.47	84	76.50	67	20
Plastics[a]	19.5	14.7	76.47	100	76.50	75	100
Inert waste	7.1	4.1	90.0 [b]	90	3.0 [b]	3	100

[a] Values of dry matter content and carbon fraction for Plastics included vinyl and rubber.
[b] Default values are from 2006 IPCC guidelines for National Greenhouse Inventories (Vol. 5).

Table 3.5 shows the GHG concentrations, emission factors (*EF*), and estimated emissions in plant A and B for MSW. When calculating CO_2 emissions, biogenic emissions were excluded, but emissions of carbon with a fossil origin in the waste were considered. The carbon with a fossil origin (CO_2 fossil fuel factor) at plant A accounted for 16.24% of emissions, while at plant B this value was 12.61%, which these values were obtained by Eqs. (3.3). The emission factors of measured CO_2, CH_4, and N_2O gases in this study 137 ± 15.9 kg CO_2 ton^{-1}, 154 ± 74 g CH_4 ton^{-1}, and 5 ± 0.7 g N_2O ton^{-1} for A facility and 131 ± 18.2 kg CO_2 ton^{-1}, 21 ± 1.8 g CH_4 ton^{-1}, and 134 ± 30 g N_2O ton^{-1} for B facility, respectively, while those of IPCC default values were 172 ± 19.9 kg CO_2 ton^{-1}, 0.2 g CH_4 ton^{-1}, and 47 g N_2O ton^{-1}, respectively.

The emissions of measured CO_2, CH_4, and N_2O gases in this study 3,468 ± 460 ton CO_2 yr^{-1}, 3.9 ± 0.23 ton CH_4 yr^{-1}, and 0.12 ± 0.06 ton N_2O yr^{-1} for A facility and 8,384 ± 894 ton CO_2 yr^{-1}, 1.35 ± 0.21 ton CH_4 yr^{-1}, and 8.61 ± 1.96 ton N_2O yr^{-1} for B facility, respectively, while those of IPCC default values were 4,339 ± 576 ton CO_2 yr^{-1}, 0.12 ± 0.0 ton CH_4 yr^{-1}, and 28.5 ± 0.85 ton N_2O yr^{-1} for A facility and 10,478 ± 1,245 ton CO_2 yr^{-1}, 0.31 ± 0.01 ton CH_4 yr^{-1}, and 72.4 ± 2.15 ton N_2O yr^{-1} for B facility, respectively. CO_2 emission could be affected by carbon content and fossil carbon content of paper and nappy as mentioned above, therefore, it was not possible to make an exact comparison of the CO_2 emission factors calculated by this study and IPCC tier 2a method, but default values of fossil carbon content for paper

and nappy were not large and might not significantly affect total emissions.

The global warming potentials (GWP) of CH_4 and N_2O are approximately 21 and 310 times that of CO_2, respectively (IPCC, 2007), which those of GWP can be applied to calculate CO_2 equivalents emission estimates. Equivalent CO_2 emissions of measured CO_2, CH_4, and N_2O gases were 3,468, 82, and 37 ton CO_2-eq yr^{-1} for A facility and 8,384, 28, and 2,670 ton CO_2-eq yr^{-1} for B facility, while those of IPCC default values were 4,339, 3, and 8,825 ton CO_2-eq yr^{-1} for A facility and 10,478, 6, and 22,432 ton CO_2-eq yr^{-1} for B facility, respectively. In addition, total emissions of CO_2 equivalents in this study were 3,587 ton CO_2-eq yr^{-1} for A facility and 11,082 ton CO_2-eq yr^{-1}, while those of IPCC default values were 13,167 ton CO_2-eq yr^{-1} for A facility and 32,916 ton CO_2-eq yr^{-1}, respectively. This result indicates that the emission factors and emissions of GHGs calculated using the IPCC default were estimated to be higher than the measured values. The total CO_2 equivalent emissions calculated from the IPCC default values at A and B facilities were approximately 3.7 and 3 times higher than those measured this study, respectively.

Interestingly, plant B emitted more CO_2 and N_2O than plant A, while the measured mean CH_4 emissions at plant A were higher than at plant B. Even though plants A and B are operated with the same stoker types, different patterns of CH_4 and N_2O emissions were obtained. This result might be due to the different NO_x removal operating systems in two facilities.

Table 3.5. The mean concentration, emission factor, and emission of CO_2, CH_4, and N_2O from MSW.

Plant	GHG	Measured concentration	Emission factor (kg GHG ton^{-1})		Emission (ton GHG yr^{-1})		Total emission[d] (ton CO_2-eq yr^{-1})	
			Default[b]	This study[c]	Default	This study	Default	This study
A	CO_2	8.1 ± 0.98 (%[a])	172 ± 19.9	137 ± 15.9	4,339 ± 576	3,468 ± 460	4,339	3,468
	CH_4	33 ± 17 (ppm_v [a])	0.0002	0.154 ± 0.07	0.12 ± 0.00	3.9 ± 0.23	3	82
	N_2O	356 ± 93 (ppb_v [a])	0.047	0.005 ± 0.001	28.5 ± 0.85	0.12 ± 0.06	8,825	37
							13,167	*3,587*
B	CO_2	9.28 ± 1.34 (%)	163 ± 22.8	131 ± 18.2	10,478 ± 1,245	8,384 ± 894	10,478	8,384
	CH_4	4 ± 0.23 (ppm_v)	0.0002	0.021 ± 0.002	0.31 ± 0.01	1.35 ± 0.21	6	28
	N_2O	9,815 ± 1,196 (ppb_v)	0.047	0.134 ± 0.030	72.4 ± 2.15	8.61 ± 1.96	22,432	2,670
							32,916	*11,082*

[a] The units of greenhouse gases (GHGs) concentration are percent (%) in CO_2, parts per million of volume (ppm_v) in CH_4, and parts per billion of volume (ppb_v) in N_2O.

[b] Default was from the parameters or values using dm, CF, and FCF from 2006 IPCC guidelines

[c] CO_2 emissions were calculated by the equation 3.4 with multiplying CO_2 fossil fuel factor and flue gas concentrations and those of emission factors were calculated by the equation 3.2 and 3.3. CH_4 and N_2O emissions and emission factors were calculated by the equation 3.1 and 3.2.

[d] Total emission was calculated in terms of daily incineration, not actual year incineration.

3.3.2 GHG emissions from commercial solid waste (CSW) and specified waste

Incineration plant C was privately owned, and handled solid waste (SW) generated within the plant itself. This facility operated a continuous fluidized bed, with an SCR NO_x removal system. The plants D to I operated continuously, but had different operating conditions, although all had an SNCR system. NO_x removal system and all incinerated specified waste such as waste plastic, organic solvent waste, synthetic polymer waste, and oil waste. In Korea, specified waste incineration increased by 24% between 2007 and 2014 (MOE, 2015). Plants D and E operated on a large scale, incinerating 161 and 288 tons day^{-1}, respectively, while plants F, G, and I treated less than 100 tons day^{-1}. The incineration facilities at plants D–I were kiln & stoker types (D, F, H, and I), stoker types (E, G, H, and I), a moving grate (F), and a rotary kiln (G). At these locations, only CH_4 and N_2O were analyzed, with no CO_2 analysis.

Table 3.6 shows that N_2O emissions were much higher than those of CH_4 in most plants. The variations in emissions were due to the differences in the operating conditions, for example, type of plant, temperature, and operating time. In addition, N_2O emissions were affected by NO_x removal systems than CH_4 emissions, which the reagent in the SNCR system may influence the conversion NO_x to N_2O.

Data of the transportation management system (TMS) were also used for the

calculation of CO_2 from commercial solid waste (CSW) and specified waste (SW) facilities (D, F, H (stoker), and I facilities), while there was TMS data available at C, E, G, and H (Kiln & stoker) (Table 3.6). The CO_2 emission factors using the TMS data were much higher than those of CH_4 and N_2O, while emissions of CO_2 equivalent were estimated to be the highest emission for N_2O gas, due to higher global warming potential (Table 3.6).

Table 3.6. The mean concentration, emission factor, and emission of CO_2, CH_4, and N_2O from commercial solid waste and specified waste.

Plant	Type of plant	Measured concentration (%)	Measured concentration (ppm_v)		Emission factor (kg CO_2 t^{-1})	Emission factor (g GHG t^{-1})		Emission (ton CO_2.eq yr^{-1})			Total emission (ton CO_2.eq yr^{-1})
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	
C	Fluidized	-	3.71 ± 0.1	15.7 ± 0.48		22.56	259.76	-	8.21	1,395	***1,403***
D	Kiln & stoker	7.34 ± 1.2	5.14 ± 0.3	18.6 ± 1.15	3,425	87.19	867.69	138	24	3,566	***3,728***
E	Stoker	-	4.67 ± 0.3	1.64 ± 0.15		57.84	55.86	-	28	397	***425***
F	Kiln & stoker	6.61 ± 0.9	3.58 ± 0.2	2.31 ± 0.37	1,748	34.44	61.11	131	17	440	588
	Moving grate	7.41 ± 0.9	-	3.62 ± 0.45	3,434	-	167.86	151	-	708	859
											1,447
G	Stoker	-	3.56 ± 0.2	3.01 ± 0.36		84.70	196.95	-	16	541	557
	Rotary kiln	-	3.48 ± 0.2	2.89 ± 0.21		84.35	192.64	-	16	530	546
											1,103
H	Kiln & stoker	-	3.68 ± 0.1	36.7 ± 2.82		55.73	1,528.29	-	23	9,381	9,404
	Stoker	7.44 ± 1.6	4.82 ± 0.2	40.6 ± 2.04	2,727	64.27	1,488.67	98	16	5,482	5,596
											15,000
I	Kiln & stoker	6.46 ± 0.8	2.65 ± 0.3	10.8 ± 0.96	2,768	41.29	462.76	137	14	2,344	2,495
	Stoker	7.67 ± 1.1	5.68 ± 0.2	12.5 ± 0.53	3,652	98.34	592.12	181	34	3,014	3,229
											5,724

3.3.3 Sensitivity analysis

A sensitivity analysis was applied to assess the impact on emission factors by the uncertainty within input parameters. In order to perform the sensitivity analysis, Monte Carlo simulation was performed 100,000 runs for a single parameter assuming that the remaining variables were constant in A and B facilities for MSW. The input variables affecting the GHG emission factors were the measured concentrations of each gases, flow rates, and incineration. For both A and B facilities, the largest contribution parameter to emission factors was the measured concentrations of each gas, and the values of percentage contribution to probability for CO_2, CH_4, and N_2O were approximately 88, 98, and 97% for A facility, and 95, 97, and 96% for B facility, respectively. The second impact on the sensitivity analysis was the flow rate, and that of the incineration was negligible (Fig.3.2).

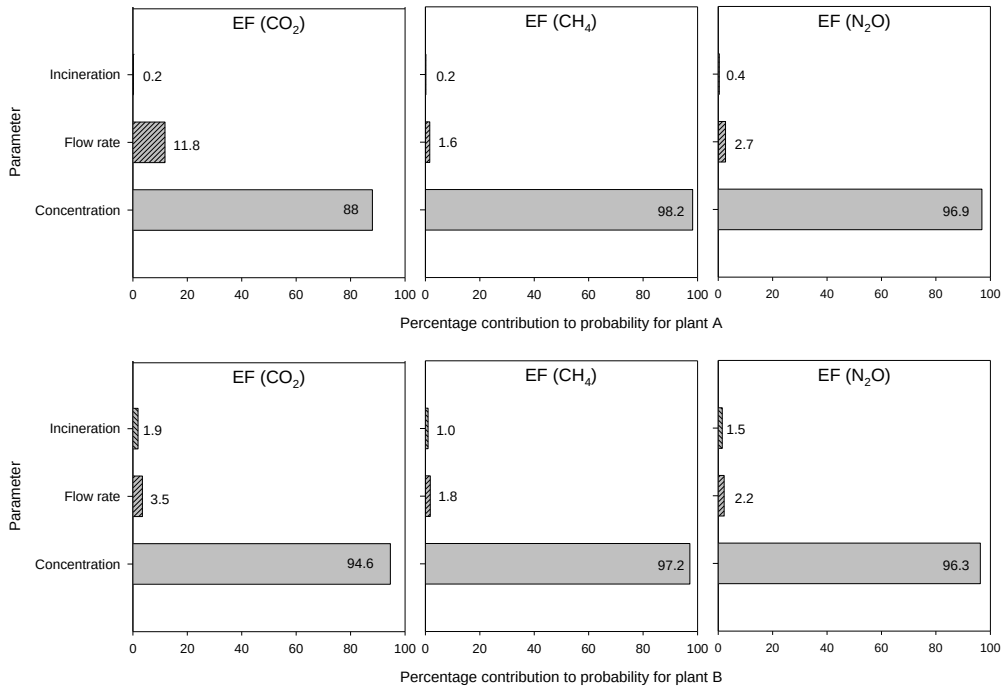

Fig. 3.2 Sensitivity analysis of emission factors using activity parameters.

3.4 Discussion

3.4.1 GHG emission factors and emissions

The amount of carbon in biogenic and fossil fuels may vary between different incineration plants and countries, while GHG emissions are also influenced by the type of plant and mode of operation, incineration operating conditions, de-NO_x systems, and other pollution control technologies. The removal efficiency of NO_x in the incineration plant differs due to the different NO_x removal systems (i.e., SCR and SNCR systems), with SNCR possibly being susceptible to the generation of N_2O emissions and its efficiency being influenced by the choice of reagent (i.e., urea, ammonia, and cyanuric acid). It is reported that, in case of urea, about 30% of the NO_x can be converted to N_2O, whereas in the case of ammonia, the maximum conversion of NO_x to N_2O is around 15% (Svoboda et al., 2006). In the SNCR process, ammonia or urea is injected upstream in the furnace at a higher temperature zone (900–1100 ℃), and NO_x reduction efficiency is 40–75% using no reactor, which the energy consumption and initial investment cost is lower than SCR, but conversion rate to NOx is high. In contrast, in SCR, ammonia is injected near combustor exit, and can reduce NOx emissions by as much as 90% operated between 250 ℃ and 350 ℃ using a catalyst reactor. Such lower temperature in SCR

than in SNCR is usually coupled with lower emissions of N_2O (Svoboda et al., 2006; Hill et al., 2000).

The CO_2 emission factors in plants A and B of MSW were similar (137 ± 15.9 kg CO_2 ton^{-1} in Plant A, 131 ± 18.2 kg CO_2 ton^{-1} in Plant B) while the CH_4 and N_2O emission factors followed the opposite trend as shown in Table 3.5. The N_2O emission factors for the incineration of specified waste in plants C–I were generally higher than those for CH_4, which might be due to country- or plant-specific factors, and the operating conditions. In addition, the emission factors and emissions calculated using the IPCC default values in the MSW were higher than those calculated in this study. Plant- and/or management-specific data are needed to estimated CO_2 emission factors for Tier 3 method in incineration facilities, but data on FCF values have not been available in Korea until now.

The ranges of the CH_4 and N_2O emission factors for the incineration of MSW and CSW were 22.56–147.69 g CH_4 ton^{-1} and 4.48–259.76 g N_2O ton^{-1}, respectively. The average of emission factors for the incineration of specified waste (SW) were 84.35 g CH_4 ton^{-1} and 192.64 g N_2O ton^{-1} (rotary kiln), which had no CO_2 data, 2,647 kg CO_2 ton^{-1}, 54.66 g CH_4 t^{-1} and 729.96 g N_2O t^{-1} (kin & stoker), and 3,189 kg CO_2 ton^{-1}, 76.29 g CH_4 ton^{-1} and 584.15 g N_2O ton^{-1} (stoker).

The CO_2 emission factors estimated in this study for MSW incineration were rather lower than those of values in Japan, Norway, and IPCC default, and the emission factors and emissions of CH_4 and N_2O in this study showed a slight deviation. The emission factors and total emissions of N_2O for specified wastes were higher than those of CH_4, which was estimated to be negligible. The variation of N_2O emission factors was large, because the treatment materials of each incineration plant are somewhat different; implying that further research on the GHG emission from specified waste sector is needed.

Data in this study can be used in the national inventory report and an emission trading scheme for GHG management and climate change mitigation. However, since GHG emissions vary greatly depending on the emission factors, it is necessary to estimate the emissions by calculating the country- and/or plant-specific emission factors.

3.4.2 Greenhouse gas emissions and energy reuse in MSW

Waste incineration plants emit greenhouse gases by burning MSW, industrial waste, commercial solid waste, hazardous waste, medical waste, and sewage sludge. Even though the GWP of CH_4 and N_2O is 21–25 and 298–310 times higher than CO_2 based on a 100–year time scale, CO_2 emissions are a significant part of incineration facilities (IPCC, 2006; Olsson et al., 2014; Li et al., 2016). Moreover, as societies or economies develop and populations grow, the proportion of incineration is increasing, and greenhouse gas emissions are also increasing. Therefore, one of the ways to reduce these greenhouse gases is to reuse the heat generated during incineration.

Table 3.7 shows the CO_2 equivalent emissions emitted by actual incineration and the energy reuse (i.e. heat and electricity production). The energy reuse of A facility increased by 6.5% from 113,723 Giga calories (Gcal) in 2007 to 121,620 Gcal in 2014, and that of B facility increased by 26.7% from 141,194 Gcal in 2007 to 192,512 Gcal in 2014, in particular, there was little difference between incineration in 2007 and 2014. The reason for the increase in energy reuse rate at B facility was considered that the energy system was improved by replacing the existing stoker incinerator with pyrolysis & melting stoker incinerator in 2010. Furthermore, the external energy supply excluding the internal use amounted to about 47% for A facility and 69% for B facility.

Total incineration facilities at MSW were 180 in 2007 and 185 in 2014. Energy reuse facilities increased from 42 in 2007 to 95 in 2014, which the energy reuse rate increased to 55.8% (MOE , 2008, 2015). Therefore, in order to reduce GHGs, it is necessary to estimate the plant-specific emission factors and reduce the greenhouse gas by replacing an old incinerator with an improved one.

Table 3.7. GHG emissions and energy reuse from actual incineration of MSW.

Year	Plant	Incineration (ton yr^{-1})	Emission[a] (ton CO_2-eq yr^{-1})		Energy re-use (Gcal yr^{-1})		Reference
			Default[b]	This study	Heat	Electricity	
2006	A	49,986	9,326	7,087	-	-	Energy supply data not available.
	B	63,904	11,348	11,054	-	-	Energy supply data not available.
2007	A	50,492	9,421	7,159	43,256	70,467	
	B	69,773	12,390	12,069	141,194	0	
2014	A	51,384	9,587	7,285	114,820	6,800	External energy supply was 47%.
	B	69,442	12,331	12,012	177,784	14,728	External energy supply was 69%.

[a] Emissions were calculated by applying the emission factors given in Table 3.

[b] Default was from the emission factors by 2006 IPCC guidelines.

3.5 Conclusions

GHG emissions were measured from the flue gases in waste incineration plants treating municipal solid waste (MSW), commercial solid waste (CSW), and specified waste (SW) for the calculation of emission factors. The results showed that the emissions of CO_2 from MSW are much higher than those from CH_4 and N_2O while CH_4 emissions were relatively negligible. The opposite pattern of CH_4 and N_2O emissions of A and B facilities in MSW might be due to the different NO_x removal systems of A (SCR) and B (SNCR), even though these facilities used the same stoker type. In addition, total GHG emissions of A and B facilities in the MSW were 14,669 ton CO_2-eq yr^{-1} in this study, compared to 46,083 ton CO_2-eq yr^{-1} in the IPCC default values, which was a threefold difference. The GHG emission from the incineration of CSW was found to be 1,403 ton CO_2-eq yr^{-1}. The total GHG emissions from the D to I facilities for SW incineration were 3,728, 425, 1,447, 1,103, 15,000, and 5,724 ton CO_2-eq yr^{-1}, respectively. The variation in GHG emissions can be due to the differences in waste types, the type of incinerator used, temperature, operating conditions, the NO_x removal system, and other technical parameters.

In Korea, since the emission factors for specified waste have not been calculated using the IPCC Tier 2, and there is insufficient information available to determine variations due to the type of plant and de-NO_x system used. Even though the data

were obtained between 2005 to 2007, since not many studies were conducted until now in Korea to estimate GHG emission factor from incineration plants based on the measured valued from the stack, the GHG emission factors obtained by this study will be helpful for providing country-specific data and national emission factors in the incineration sector in Korea.

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Chapter 4. Greenhouse gas emission factors for wastewater treatment and incineration facility – A review

4.1 Introduction

The study of gaseous emission, climate change and air pollution is committed to physico-chemical identification, inventories, measurements and assessment methods as well as on quantitative study of the actual anthropogenic sources and its direct contributions (Listowski et al., 2011). A large body of scientific literature shows that stabilizing global temperatures requires a limit on the cumulative amount of long-lived greenhouse gases emitted to the atmosphere (Rogelj et al., 2012).

Greenhouse gases are emitted in a variety of fields, including energy, industrial processes, agriculture, forests, and waste, which is affecting ecosystems such as global warming, climate change, and indirect social-economic change. Greenhouse gas emissions are also generated in wastewater treatment and incineration facilities in the waste sector, and are currently included in the national inventory report. Annex I Parties submit National Inventory Report (NIR) and Common Reporting Format (CRF) to United Nations Framework Convention on Climate Change (UNFCCC) covering emissions and removals of direct GHGs (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons

(HFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) from five sectors (energy; industrial processes and product use; agriculture; land use, land-use change and forestry (LULUCF); and waste), and for all years from the base year (or period) to two years (UNFCCC), and at Conference of Parties (COP) 13, through the Bali Action Plan, developing country parties including Korea implement through national communications (NCs) and biennial update reports (BURs) including an update on their national GHG inventories, information on mitigation actions according to the 2006 IPCC guidelines for National Greenhouse Gas Inventories (2006 IPCC guidelines) and Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (GPG 2000). As mentioned in Chapter 1, According to the International Energy Agency's 'CO_2 Emissions from Fuel Combustion Highlight 2016' report (IEA, 2016), worldwide CO_2 emissions (138 countries) from fossil fuel combustion were 20,503 million tons in 1990 and 32,381 million tons in 2014, an increase of 1.6 times in 2004 compared to 1990. CO_2 emissions from fossil fuel combustion in Korea amounted to 231.7 million tons in 1990, 17th in the world, while in 2014, it was 7th in the world with 567.8 million tons (Fig. 4.1).

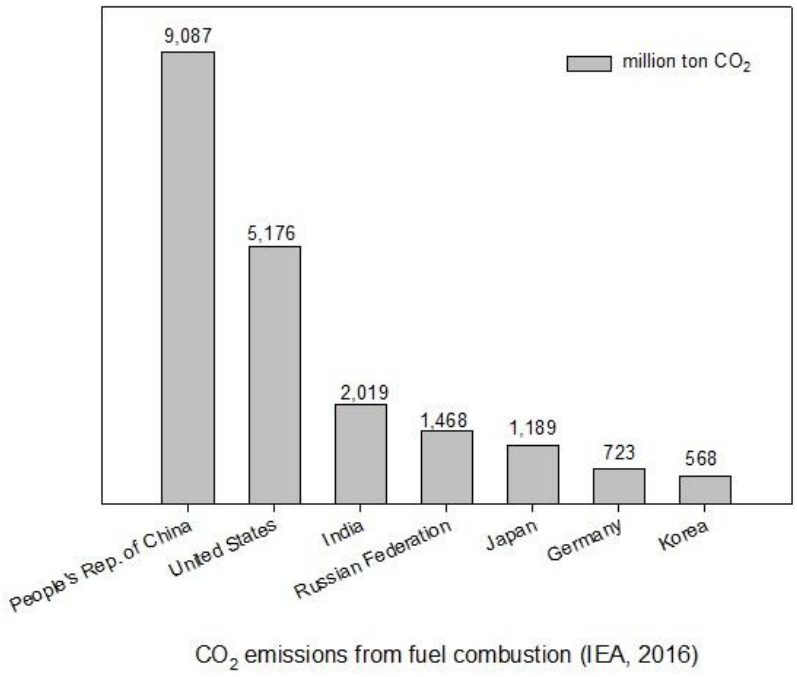

Fig. 4.1 CO_2 emissions from fuel combustion in 2014 (IEA, 2016).

According to the National Inventory Report (2016) in Korea, total GHG emissions in 2014 were 690.6 million tons of CO_2-eq, which increased by 135.6% from the total of 293.1 million tons of CO_2-eq in 1990 and decreased by 0.8% of the total emissions of emissions of 696.5 million tons of CO_2-eq in 2013, respectively. GHG emissions in the waste sector in 2014 amounted to 15.4 million tons of CO_2-eq, accounting for 2.2% of total national emission, an increase by 47.8% compared to 1990 and decreased 3.3% from 2013. In waste sector, emission portion of waste landfill accounted for 47.5%, waste incineration was 41.1%, wastewater treatment was 9.2%, and other sector was 2.2%. And CO_2 emissions in 2014 were 628.8 million tons CO_2-eq, accounting for 91.1% of total emissions. Non-CO_2 greenhouse gases accounted for 3.9% of CH_4, 2.2% of N_2O, 1.2% of HFCs, 1.4% of SF_6, 0.4% of PFCs. Looking at sub-sectoral emissions in the waste sector, GHG emissions from the incineration surged by 465% over the period 1990–2001, reaching a peak of 8.1 million tons CO_2-eq in 2001 and then falling. However, as the waste recycling and renewable energy sectors were activated based on the governmental plan in 2001, the GHG amount of incineration was reduced.

Greenhouse gas emissions are calculated by multiplying the activity data by the emission factors, which usually used the three tiers concepts. Tier 1 is the basic method using default values provided by 1996, 2006 IPCC guidelines, and GPG 2000. Tier 2 is intermediate method, which combined with default emission factors of IPCC guidelines and country-specific emission factors. Tier 3 is higher

complexity method using plant-specific emission factors.

Wastewater treatment can also produce greenhouse gases in process of biological treatment and waste incineration facilities produce greenhouse gases with containing fossil carbon, e.g. plastics, are the most important sources of CO_2 emissions. In the present study, an attempt has been made to provide a comprehensive review of wastewater treatment and incineration facilities to evaluate the current status and identify the problems. This will be done by studying the wastewater treatment process-treatment and incineration facilities for greenhouse gas emissions and emission factors.

In the wastewater treatment plants, CO_2 emission in wastewater treatment is biogenic, so it is excluded from the total emissions. Methane emission estimation methodology of 2006 IPCC guidelines is divided into sewage and industrial wastewater as in the 1996 IPCC guidelines and GPG 2000. Compared with the 1996 IPCC guidelines and GPG 2000 methodology, 2006 IPCC guidelines are no significant methodological change in wastewater treatment, but the “fraction of population in income group (U) and “degree of utilization of treatment/discharge pathway or system (T)” have been added (see the equations of chapter 1). And N_2O emission in wastewater treatment was calculated by nitrogen in the effluent discharged to aquatic environment and emission factor based on nitrogen parameter.

In the incineration facilities, greenhouse gas emissions are affected by operation types such as fixed grate, rotary-kiln, fluidized bed, specialized

incineration such as mixed types of incineration, and de-NO_x system, technology for incineration and conditions during the incineration process. As a mentioned above (chapter 1), Normally, N_2O is affected by emissions depending on the de-nitrogen system such as SNCR, SCR, and complex denitrification system.

In the CO_2 estimation of incineration facilities, biomass materials (such as paper, food, and wood waste) should not be included in total emissions. CO_2 emissions were composed of parameters such as fraction of carbon content, fraction of fossil carbon, and burn out efficiency of combustion of incinerators in the GPG 2000, while in the 2006 IPCC guidelines, dry matter content and oxidation factor were added instead of incineration efficiency.

This chapter was focused on greenhouse gas emission factors by various countries and researches, and assessing/comparing with other studies and suggest deficiency and assignment according to this study and other researches, and discuss the limitation of this study and future directions for the measuring the GHG emissions and calculation the emission factors in wastewater treatment plants and incineration facilities.

4.2 Methods

A systematic article search was conducted to trace the relevant existing study, using the keywords in online academic databases and search engines, such as ‘greenhouse gas’, ‘emission factor’, wastewater treatment’, and ‘incineration’. Articles relevant to the scope of the work were collected by using the document review papers containing the regulatory framework texts, academic articles, technical documents. The regulatory literatures were contained with greenhouse gas emissions and emission factors for plant-specific or country-specific. Technical documents were categorized as sampling methods for wastewater using chamber technique. This study was performed by mixing research method, as syntheses of both qualitative and quantitative information with understanding the estimation of emission factors. Greenhouse gas emissions and emission factors in wastewater treatment and incineration facilities were reviewed in the NIR and CRF submitted to UNFCCC and research papers including NIR of Korea. And methodologies of IPCC guidelines were presented in chapter 1 and Appendix.

Under anaerobic conditions, the sewage organic materials decomposes from a complex matter to a simple one through a gradual process, starting with the hydrolysis of complex particulate matter to simpler polymers like proteins, carbohydrates and lipids that are further hydrolyzed to yield bio monomers like amino acids, sugars, and high molecular fatty acids, amino acids and sugars are

converted into either intermediate by-products (e.g. propionic, butyric and other volatile acids) or directly fermented to acetic acid. High molecular fatty acids are oxidized to intermediate by-products and hydrogen. Methane and carbon dioxide production occurs through acetate cleavage. Methane is also produced through carbon dioxide reduction with hydrogen (El-Fadel and Massoud, 2001).

A method for determining the extent of methane production is to convert into basis of the amount of degradable organic fraction by biochemical or chemical oxygen demand (BOD) or (COD). Main parameters that influence methane production are temperature, pH, retention time, degree of anaerobic treatment, competition between methanogens and sulfate reducing bacteria, and toxicants. In particular, anaerobic conditions are very important with production of methane.

The removal of nitrogen nutrients is very important in wastewater treatment. Biological treatment processes are widely used in removal of nitrogen and other pollutions because of its high efficiency and low cost. The conventional biological nitrogen removal processes include autotrophic nitrification, which oxidizes ammonium via nitrite to nitrate by nitrifying bacteria under aerobic conditions, and heterotrophic denitrification, which converts nitrite and nitrate to N_2 gas by denitrifying bacteria under anaerobic conditions (Duan et al., 2015).

Nitrification is performed by three different groups of micobes; ammonium-oxidizing bacteria and archaea that convert ammonia into nitrite, and nitrite-oxidizing bacteria that convert nitrite into nitrate (Fig. 4.2). In WWTPs

nitrification is assumed to be predominantly performed by autotrophic bacteria that use ammonia or nitrite as their energy source and CO_2 as carbon source. Ammonia oxidation can also be performed by heterotrophic bacteria. Although there are no indicates that heterotrophic ammonia oxidizes or ammonia oxidizing archaea play a significant role in conventional activated sludge plants, which still might be significant in the production of nitrous oxide (Kampschreur et al., 2009).

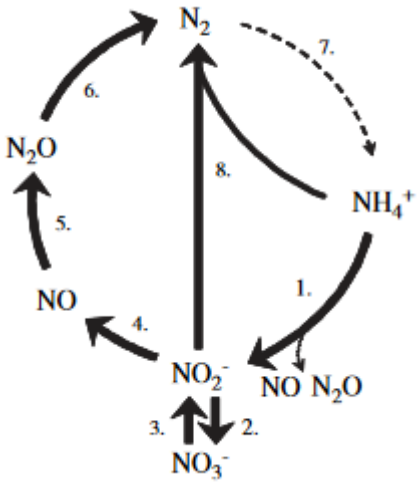

Fig. 4.2 Biological nitrogen conversions (Kampschreur et al., 2009). (1) Aerobic ammonia oxidation, (2) aerobic nitrite oxidation, (3) nitrate reduction to nitrite, (4) nitrite reduction to nitric oxide, (5) nitric oxide reduction to nitrous oxide, (6) nitrous oxide reduction to dinitrogen gas, (7) nitrogen fixation (not relevant in most WWTPs), (8) ammonium oxidation with nitrite to dinitrogen gas. Complete nitrification comprises step 1 and 2, complete denitrification step 3-6.

4.3 Results and discussion

4.3.1 Review of greenhouse gas emission factors from the Wastewater treatment facility

Wastewater is also the source of CH_4 and N_2O when treated anaerobically, which CO_2 emissions are excluded because of biogenic origin and should not be included in national total emissions. Wastewater originates from domestic, commercial and industrial sources, which treated by physical, chemical and biological treatment processes. Sewer system may vary by country, region, and operating system. The most common wastewater treatment methods in developed countries are centralized aerobic wastewater treatment plants and lagoons for both domestic and industrial wastewater (IPCC, 2006).

Centralized wastewater treatment methods are classified as primary, secondary, and tertiary treatment. Wastewater can come from washing water, rainfall runoff, and wastewater produced by many kinds of human activities. Pretreatment removes all materials using grit. Primary treatment is used to settle sludge while grease and oils rise to the surface and are skimmed off. Secondary treatment can degrade the biological content of the wastewater which is come from human waste using aerobic biological processes, which types are activated sludge, aerated granulation,

constructed wetland, membrane bioreactor, Sequencing batch reactor, and other types of processes. Tertiary treatment is to provide a final treatment stage to improve the effluent quality by eliminating nutrients (phosphorus and nitrogen). Sludge also can be produced in all processes, which treated using digestion.

Table 4.2 shows an overview of the methodology for measuring CH_4 and N_2O gas in various wastewater treatment plants, and represents emission factors for CH_4 and N_2O gas in various researches. Emission factors for CH_4 and N_2O in the wastewater treatment processes vary according to each treatment method (Table 4.3). Emission factors in biological treatment, advanced treatment and sludge treatment show various deviations and the highest emission factor in sludge treatment. In the 2006 IPCC guidelines, CH_4 emission factor was calculated by multiplying maximum CH_4 producing capacity (B_o; kg CH_4/kg BOD) and methane correction factor (MCF; fraction). Furthermore, the CH_4 emissions in the 2006 IPCC are estimated by per person using correction factors, whereas N_2O emission factor is 5 g N_2O/kg TKN, which is higher than those in this study.

The emission factors as a final result represents the average value of the emission factors from all the reactors/basins in the wastewater treatment plant. Table 4.1 shows a comparison of the emission factors in wastewater treatment plants with activated sludge treatment. In this study and Kwon et al. (2007), sampling was performed in the same WWTP, and NIER (2007) was performed in K plant including pH adjustment tank and flocculation tank before the aeration tank, which

treated with domestic and manure sewage. And even if the emission factors of NIER (2007) were different units, the patterns and aspect can be examined. In this study, measuring in grit chamber was not performed. In the case of CH_4 gas of this study, the emission factor was high in the order of sludge thickener, aeration, secondary settling, and first settling tank, while in Kweon et al. (2007) study, first settling, aeration, secondary settling, and sludge thickener tank were higher, but sludge thickener tank showed almost little value. The reason for the large variation in the emission factor, even though it was measured in the same WWTP, the gas was collected in the flux chamber modified forced-draught chamber and analyzed at the laboratory in this study, while in the case of Kweon et al. (2007) study, it was directly analyzed by NDIR in the field. In the first/secondary settling tank, the scrubber was moving at regular time intervals, which may cause considerable difficulty in stabilizing the NDIR during the field analysis. For this reason, it is considered that there might be a considerable difference from the values in this study. In the Wang et al. (2011) study, the CH_4 emission factor for the sludge digestion tank was the largest excluding advanced treatment basins. N_2O emission factors also showed different patterns and large variation like those of CH_4. In the Lim and Kim (2014) study, N_2O emission factor was highest at the aeration tank, and that of first settling tank was smaller than secondary settling tank. Therefore, the CH_4 and N_2O emission factors in this study were similar to those of pattern from “Wang et al. (2011)” and “Lim and Kim (2014)” studies. So the CH_4 and N_2O emission factors in

this study were considered valid.

The CH_4 emission factors in WWTP (Table 4.3) ranges from approximately 3 to 21 g CH_4/kg BOD_5, and that of N_2O ranges from approximately 1 to 28 g N_2O/kg TN. The CH_4 emission factors in MOE (2000) was calculated by multiplying maximum methane producing capacity (B_o: 0.25 kg CH_4/kg BOD), anaerobically treatment rate (10%), and methane correction factor (MCF, 80.48%) from the equation of 2006 IPCC guidelines. Here, MCF was calculated by averaging the measured values at Jungryang plant (88.94%) and Gwacheon plant (72.02%).

B_o value of 2006 IPCC guidelines represents 0.6 kg CH_4/kg BOD and 0.25 kg CH_4/kg COD for domestic wastewater, while B_o of MOE (2000) study was 0.25 kg CH_4/kg BOD, which there was an error in calculating the emission factor.

In MOE (2002) study, the sampling was performed by closed flux chamber method. Sampling sites in Gwanju plant were grit chamber, sludge thickener, and inlet of biogas storage tank. Those of Hwasun plant were sludge thickener, secondary settling tank, and rotary biological contactor. Such sampling sites showed that missing sites such as aeration tank and first settling tank should be contained in calculating emission factors. And emission factors at each basin were not presented and the average emission factor of two plants was presented. It was not possible to evaluate the effect on the four seasonal analyses, and the emission factor was overestimated because two plants included manure treatment.

In NIER (2007) study, the sampling was performed by dynamic flux chamber method. Sampling sites in K plant were first settling, aeration, and secondary settling tank, which were missed in sludge thickener, and included manure treatment. And emission factors (1.61 g CH_4/kg BOD (336.76 mg CH_4/m^3) and 2.65 g N_2O/kg TN (36.12 mg N_2O /m^3) were smaller than those of Japan (WWTP: 528.7 mg CH_4/m^3 and 142 mg N_2O /m^3), which the reason was the missed in sludge thickener and grit chamber.

In Daelman et al. (2013) study, the emission factors were 11 g CH_4/kg COD and 28 g N_2O/kg TN, which the reason was not BOD based but COD based, and sample analysis was directly colliection of off-gas by Servomex 4900 infrared gas analyzer with difficult stabilization on wastewater surface.

In KEC (2006) and MOE (2016), CH_4 emission factor (15.32 g CH_4/kg BOD) was an average value by MOE (2000) and MOE (2002) in WWTP. And this emission factor is applied to calculate emission inventory for facilities in Target Management Scheme and Emission Trading Scheme. The CH_4 emission factor of anaerobic digester for sludge was 480 g CH_4/kg BOD, which the value were calculated by multiplying Bo (0.6 kg CH_4/kg BOD) and MCF (0.8) by the 2006 IPCC guidelines, and calculated to be much larger than the range shown in Table 4.3 and overestimated. KEC (2013)'s emission factor for CH_4 and N_2O gas were represented as national emission factor but this values are not currently in use, and it is also necessary to calculate national emission factors from more plant-specific data.

The CH_4 emission factors for advanced treatment such as A^2O, bardenpho, Sequential batch reactor, etc. ranges approximately 0.5–277 g CH_4/kg BOD, and those of N_2O ranges approximately 0.5–715 g N_2O/kg TN. The reasons depend on sampling method, analysis method, wastewater treatment process, operating condition, and inflow materials. And also in the Sludge digestion tank, the CH_4 emission factors ranges from 189 to 227 g CH_4/kg BOD, while those of N_2O have almost little emission factor (Table 4.2 and 4.3). Therefore, in order to calculate the national emission factors, it is considered that more similar treatment plant data would be needed.

In Japan's NIR, various emission factors for CH_4 and N_2O were represented, but most of countries calculate emissions using method 2006 IPCC guidelines such as B_o and MCF.

In Korea (NIR), the emission factors of wastewater treatment were 15.32 g CH_4/kg BOD for physical treatment, 18 g CH_4/kg BOD for biological treatment, and 7.1 g CH_4/kg BOD for advanced treatment from emission factors calculated based on MOE (2000, 2002) and KEC (2006) , which also necessary to calculate national emission factors from more plant-specific data.

In MOE (2002) study, CH_4 emissions from Gwanju sewage treatment plant were highest in summer in grit chamber, in spring in first settling tank, and winter in sludge thickener, which were different according to the type of reactor/tank. CH_4 emissions from Hwasun sewage treatment plant were highest in the secondary

settling tank and sludge thickener in the summer. N_2O emissions from Gwanju sewage treatment plant were highest in autumn in grit chamber, in winter in first settling tank, and autumn in sludge thickener, and those from Hwasun sewage treatment plant were highest in spring in the secondary settling tank, and in autumn in sludge thickener. Thus the seasonal effect had no same pattern for the season for the CH_4 and N_2O emissions, and those of emissions were not consistent with season. Thus, as shown in Table 4.2, there was insufficient and further research is needed.

Table 4.1. Comparison of emission factors for WWTP.

CH_4	Grit chamber	First settling	Aeration	Secondary settling	Sludge thickener	Unit
This study		0.258 ± 0.09	0.720 ± 0.63	0.670 ± 0.31	2.086 ± 0.18	g CH_4/kg BOD_5
Kwon et al. (2010)	0.07	2.30	2.05	0.17	0.02	g CH_4/kg BOD_5
NIER (2007)[a]		162.83	168.38[b]	0.63	-	mg CH_4/m^3
N_2O						
This study		0.263 ± 0.03	0.672 ± 0.37	0.226 ± 0.01	0.195 ± 0.09	g N_2O/kg TN
Kwon et al. (2010)	0.06	1.86	2.22	0.09	0.01	g N_2O/kg TN
NIER (2007)		2.71	8.71	14.49	-	mg N_2O/m^3

[a] K plant was treated with domestic wastewater and excretion leachate.

[b] Measuring sites were at influent and effluent places of aeration basin, the value of effluent place because was assumed as influent value of secondary settling basin.

Table 4.2. Estimation method (CH_4 and N_2O) for wastewater treatment.

	Treatment process	Sampling site	Sampling method	Analysis	Season	Reference
South Korea						
This study	WWTP[a]	First/secondary settling, aeration basin, and sludge thickener	Dynamic flux chamber	CH_4: GC FID N_2O: GC ECD (Lab.)	Winter (November/ December)	Jungryang plant
	A^2O	Anaerobic/anoxic/aerobic	Dynamic flux chamber	As above	As above	As above
	Sludge digestion tank	Sludge digestion tank and gas outlet	Sludge and gas collection	As above	As above	As above
Kwon et al. (2010)	WWTP	Grit chamber/ first/secondary settling, aeration basin, and sludge thickener	Dynamic flux chamber	NDIR (On-site)	Autumn (October)	Jungryang plant
	Sludge digestion tank	Operation data	Calculation	-		U.S.A. NIR method
Lim and Kim (2014)	Batch reactor	Primary clarifier/pre-anoxic/ anaerobic/anoxic/aerobic/ secondary clarifier	Direct collection of off-gas from basins	N_2O: GC ECD (Lab.)	-	Laboratory scale batch reactor
O et al. (2009)/ MOE (2008)	Modified Ludzack Ettinger (MLE) and A^2O	A^2O (4^{th} basin) and MLE (5^{th} and 6^{th} basin (food waste leachate))	Dynamic flux chamber	NDIR (On-site)	Autumn (October/ November)	A plant in Incheon city (Advanced treatment)

Table 4.2. Continued.

	Treatment process	Sampling site	Sampling method	Analysis	Season	Reference
Yang. et al. (2008)	Denipho	Anaerobic/intermittent aeration/aeration/ anaerobic/ intermittent aeration/aeration basin	Dynamic flux chamber	N_2O: GC ECD (Lab.)	No data	Average value (including excretion leachate), No data for sampling plant
	5-stage	Anaerobic/anoxic/ aerobic /anoxic/aerobic basin	As above	As above	No data	
	Sequential batch reactor (SBR)	Aerobic/anaerobic/ aerobic/ anaerobic basin	As above	As above	No data	As above
	WWTP	First/secondary settling, aeration basin	As above	As above	No data	As above
MOE (2000)	WWTP	Calculation	B_o, MCF(measured)	2006 IPCC GL. method	-	Jungryang and Gwacheon plants
MOE (2002)[c]	WWTP: Gwangju	Grit chamber/ sludge thickener/ Inlet of biogas storage	Dynamic flux chamber	CH_4: GC FID N_2O: GC ECD (Lab.)	Four seasons	Average value (including excretion leachate)
	WWTP: Hwasun	Secondary settling/sludge thickener/rotary disc contact tank		As above	As above	As above
NIER (2007)	WWTP	First/secondary settling, aeration basin	Dynamic flux chamber	CH_4: GC FID N_2O: GC ECD (Lab.)	Early summer/ Autumn	K plant
	SBR	Aerobic/anaerobic/ aerobic/ anaerobic basin		As above	As above	D plant
	Denipho	Intermittent aeration/aeration basin/aerobic		As above	As above	H plant
	5-stage	Anaerobic/anoxic/ Aerobic/anoxic/aerobic basin		As above	As above	Y plant

Table 4.2. Continued.

	Treatment process	Sampling site	Sampling method	Analysis	Season	Reference
Other countries and researches						
Daelman et el. (2013)	WWTP	Primary settler/storage tank for primary sludge/buffer storage tank for digester effluent	Direct collection of off-gas	Servomex 4900 infrared gas analyser	Autumn/ winter	In Netherlands
Yan et al. (2014)	Orbal oxidation ditch	Grit chamber/orbal oxidation ditch/secondary settling/sludge storage tank	Closed flux chamber	CH_4: GC FID N_2O: GC ECD	March-November	In Beijing
	Reversed A^2O	Anoxic/anaerobic/aerobic				
	A^2O	Anaerobic/anoxic/aerobic				
Wang et al. (2011)	A^2O	Anaerobic/anoxic/aerobic	Flux hood technique	CH_4: GC FID	March-June	In Jinan
Foley et al. (2010)	BNR	Primary settler/anoxic/aerobic/secondary settler	Flux hood technique	N_2O: GC ECD	Winter/ spring (5 month)	In Australia
Oshita et al. (2014)	Sludge digestion[d]	Sludge digestion and dewatering	Closed flux chamber	CH_4: GC FID N_2O: GC ECD (Lab.)	Winter/ summer	In Japan

[a] The biological treatment (the activated-sludge treatment).

[b] Five-stage Bardenpho processes with primary and secondary clarifiers.

[c] Gwangju and Hwasun wastewater treatment plants were treated with domestic wastewater and manure by 61.8% rate of total treatment, and Gwangju plant had a standard activated-sludge treatment and Hwasun plant had rotary disc method.

[d] The anaerobically digested sludge with digestion tank and dewatering system.

Table 4.3. Emission factors for wastewater treatment.

	Treatment process	CH_4	Unit	N_2O	Unit	Reference
South Korea						
This study	WWTP[a]	3.734 ± 1.21	g CH_4/kg BOD_5	1.256 ± 0.50	g N_2O/kg TN	
	A^2O	4.022 ± 0.124	g CH_4/kg BOD_5	1.605 ± 0.15	g N_2O/kg TN	
	Sludge digestion tank	227.0 ± 23.53	g CH_4/kg BOD_5	0.012 ± 0.01	g N_2O/kg TN	
Kwon et al. (2010)	WWTP	4.61	g CH_4/kg BOD_5	4.24	g N_2O/kg TN	
	Sludge digestion tank	189.9	g CH_4/kg BOD	-	-	Calculation using U.S.A. NIR method
Kyung et al. (2015)	Bardenpho	277.3	g CH_4/kg BOD	715	g N_2O/kg TN	
O et al. (2009)/ MOE (2008)	Modified Ludzack Ettinger (MLE) and A^2O	108.9[b] 45.17[c]	g CH_4/kg BOD_5	41.4	g N_2O/kg TN	
Yang. et al. (2008)	Denipho	-	-	68.17	mg/m^3	
	5-stage	-	-	73.63	mg/m^3	
	Sequential batch reactor (SBR)	-	-	644	mg/m^3	
	WWTP	-	-	8.64	mg/m^3	
KEC (2013)	WWTP	20	g CH_4/kg BOD	13	g N_2O/kg TN	Not used.
	Advanced treatment	8.1	g CH_4/kg BOD	7.5	g N_2O/kg TN	Not used.
MOE (2000)[d]	WWTP	20.7	g CH_4/kg BOD	-	-	
MOE (2002)	WWTP	9.948	g CH_4/kg BOD	1.7401	g N_2O/kg TN	
KEC (2006)		15.32[e]	g CH_4/kg BOD			Calculation
MOE (2016)		15.32 0.48[f]	g CH_4/kg BOD	0.005[f]	g N_2O/kg TN	2016 Guidelines of Korea

Table 4.3. Continued.

	Treatment process	CH_4	Unit	N_2O	Unit	Reference
NIER (2007)	WWTP	1.61	g CH_4/kg BOD	2.65	g N_2O/kg TN	
		336.76	mg CH_4/m^3	36.12	mg N_2O/m^3	Unit: mg/m^3
	SBR	4.14	g CH_4/kg BOD	26.73	g N_2O/kg TN	
	Denipho	2.88	g CH_4/kg BOD	9.30	g N_2O/kg TN	
	5-stage	0.57	g CH_4/kg BOD	0.94	g N_2O/kg TN	
Korea (NIR)	Physical treatment	15.32	g CH_4/kg BOD	-	-	N_2O: IPCC equation
	Biological treatment	18	g CH_4/kg BOD	-	-	
	Advanced treatment	7.1	g CH_4/kg BOD	-	-	
Other countries and researches						
Daelman et al. (2013)	WWTP	11	g CH_4/kg COD	28	g N_2O/kg TKN	Including sludge dewatering
Yan et al. (2014)	Orbal oxidation ditch	3.3	g CH_4/kg COD	3.6	g N_2O/kg TN	
	Reversed A^2O	1.4	g CH_4/kg COD	2.3	g N_2O/kg TN	
	A^2O	0.9	g CH_4/kg COD	0.8	g N_2O/kg TN	
Wang et al. (2011)	A^2O	11.3	g CH_4/person/yr	-	-	
Foley et al. (2010)	BNR	-	-	0.035 ± 0.027	kg N_2O/kg N	
Oshita et al. (2014)	Sludge digestion	509 ± 72	mg/m^3-influent	7.1 ± 2.6	mg/m^3-influent	
Germany (NIR)	Wastewater treatment	B_o, MCF		IPCC equation		2006 IPCC equation
U.S.A. (NIR)	Domestic wastewater	B_o, MCF		IPCC equation		2006 IPCC equation

Table 4.3. Continued.

	Treatment process	CH_4	Unit	N_2O	Unit	Reference
Japan (NIR)	WWTP (wastewater)	528.7	mg CH_4/m^3	142	mg N_2O/m^3	N_2O: standard activated sludge process
	WWTP (sludge treatment)	348	mg CH_4/m^3	0.6	mg N_2O/m^3	
	WWTP/ sludge treatment	-	-	29.2/ 0.6	mg N_2O/m^3	Anaerobic-aerobic activated sludge process
	WWTP/ sludge treatment	-	-	11.7/ 0.6	mg N_2O/m^3	Anaerobic-anoxic-oxic process and recycled nitrification; denitrification process
	WWTP/ sludge treatment	-	-	0.5/ 0.6	mg N_2O/m^3	Recycled nitrification-denitrification membrane bioreactor
United Kingdom	WWTP	B_o, MCF	-	IPCC equation	-	2006 IPCC equation
Canada	WWTP	B_o, MCF	-	IPCC equation	-	2006 IPCC equation
Switzerland	WWTP	B_o, MCF	-	IPCC equation	-	2006 IPCC equation
2006 IPCC	WWTP	B_o, MCF	-	5	g N_2O/kg TN	Default (2006 IPCC)

[a] The biological treatment (the activated-sludge treatment).

[b] The value including CH_4 of sludge digestion tank.

[c] The value excluding CH_4 of sludge digestion tank.

[d] The EF was calculated by multiplying maximum methane producing capacity (B_o: 0.25 kg CH_4/kg BOD), anaerobically treatment rate (10%), and methane correction factor (MCF, 80.48%) from the equation of 2006 IPCC guidelines.

[e] The emission factors were average value from two wastewater plants (9.948 g CH_4/kg BOD) and 20.7 g CH_4/kg BOD (MOE, 2000). CH_4 emission factor (0.01532 kg CH_4/kg BOD) is applied to the 'Greenhouse Gas, and Energy Target Management System (TMS)' and Emission Trading Scheme (ETS) at wastewater treatment plants of South Korea according to the Guidelines for Greenhouse gas and energy target management (MOE, 2016).

[f] The value is from the 2006 IPCC guidelines.

4.3.2 Review of greenhouse gas emission factors from waste incineration facility

Waste incineration is a waste treatment process of the combustion of solid, organic, and liquid substances in controlled incineration facilities. Waste materials change the waste into ash, flue gas, and heat with fossil and biogenic GHG emissions, which the energy recovery can be used to generate electric power and CO_2 emissions are more significant than CH_4 and N_2O emissions. Incineration contributes to reducing the volume of waste in area where landfills are scarce. Waste types include municipal solid waste (MSW), commercial solid waste, industrial waste, hazardous waste, medical waste and sewage sludge. The types of incinerators are moving grate, fixed grate, rotary kiln, stoker, fluidized bed, and so on. CO_2 emissions of fossil fuel origin during incineration should be included in the national emission estimate. The emissions on a plant-specific or plant-by-plant basis can be accurate for each waste using each emission factor of categories. Tier 3 is the estimate GHG emissions from plant-specific data, Tier 2b is the estimate GHG emissions using country-specific data and emission factors, Tier 2a is the estimate GHG emissions using country-specific data and default emission factors, and Tier 1 is the estimate GHG emissions using the total amount estimated and default data on emission factors (IPCC, 2006).

Incineration is a process of waste treatment that is related with the combustion

of solid and liquid substances in controlled incineration facilities. Energy recovery of incineration is waste-to-energy (WTE), which produce electricity and/or heat directly combustion. Emissions from waste incineration without energy recovery are reported in the waste sector, while emissions from incineration with energy recovery are reported in the energy sector in the 2006 IPCC guidelines. In the national inventory submissions of United Nations Framework Convention on Climate Change (UNFCCC), energy recovery countries of the Annex I Parties calculate the emissions from waste incineration in the energy sector. For example, In Switzerland's national inventory report, in accordance with the 2006 IPCC guidelines emissions from waste-to-energy activities, where waste is used as an alternative fuel for energy production, are reported in fuel combustion activities. This applies to municipal solid waste incineration plants and special waste incineration plants, where energy is recovered, as well as to the cement industry, where special waste and sewage sludge are used as an alternative fuels (NIR FOEN, 2015).

In 2006 IPCC guidelines and GPG 2000, for waste incineration, the most accurate emission estimates can be developed by determining the emissions on a plant-by-plant basis and/or differentiated for each waste category (e.g., MSW, sewage sludge, industrial waste, and other waste including clinical waste and hazardous waste). CO_2 emissions from oxidation, during incineration in waste of fossil carbon (such as plastics, certain textiles, rubber, liquid solvents, and other fossil materials) are

considered net emissions for CO_2 emission estimate, while those of biomass materials (such as paper, food, and wood waste) should not be included in total emissions. The equation for CO_2 emissions in the solid waste incineration was represented in chapter 1, which used by emission factors of dry matter content (dm), total carbon content (CF), total fossil carbon fraction (FCF), and oxidation factor assumed that is completely burned (100%). Table 4.4 shows the CO_2 emission factors for the solid waste sector, which represented by 2006 IPCC guidelines and also used as a Tier 1 emission factors for Target Management Scheme and Emission Trading Scheme in South Korea (MOE, 2016), which CO_2 emissions were calculated by multiplying those emission factors or parameters.

Table 4.4. Default emission factor of CO_2 for the solid waste.

Municipal/domestic solid waste				Industrial solid waste			
Waste component	dm	CF	FCF	Waste component	dm	CF	FCF
Paper/cardboard	0.9	0.46	0.01	Food, beverages and tobacco	0.4	0.15	0
Textile	0.8	0.5	0.2	Textile	0.8	0.4	0.16
Food	0.4	0.38	0	Wood and wood products	0.85	0.43	0
Wood	0.85	0.5	0	Pulp and paper	0.9	0.41	0.01
Garden/Yard, park waste	0.4	0.49	0	Petroleum products, solvents, plastics	1	0.8	0.8
Nappies	0.4	0.7	0.1	Rubber	0.84	0.56	0.17
Rubber and Leather	0.84	0.67	0.2	Construction and demolition	1	0.24	0.2
Plastics	1	0.75	1	Other	0.9	0.04	0.03
Metal	1	-	-	Sewage sludge	0.1	0.45	0
Glass	1	-	-	Industrial wastewater sludge	0.35	0.45	0
Other, inert waste	0.9	0.03	1	Clinical waste	0.65	0.4	0.25

In Jang et al. (2008) study, emission characteristics of CO_2 were studied in waste incineration facilities. As shown in Table 4.5, activity data for calculation CO_2 emissions and emission factors were obtained from MOE (2002) and NIER (2006) by methodology of 2006 IPCC guidelines. The values of fossil carbon content (FCF) and oxidation factor (OF) were used of 2006 IPCC default. Emissions of food, paper, wood, and rubber in MSW were calculated to have no emissions, and plastic was used as the activity data for the sum of MSW, industrial waste, and construction waste. The amount of synthetic textile/rubber/leather/polymer was the activity data from industrial waste, construction waste, and hazardous waste, not domestic waste. Other waste was the total amount of food, paper, wood, rubber/leather, and synthetic resin in MSW. The CO_2 emission factor of MSW was estimated to be 565 kg CO_2/ton-waste of 'Other waste', which the incineration efficiency was 98% suggested by MOE (2002), and operation day was 365 days not actually average operation days. Such emission factors were likely to be overestimated because of the sum of activity data from various waste sectors. Emission factors in Table 4.5 for CO_2 was calculated without distinguishing the type of waste, and were not appropriate to use them as the national emission factor data of Korea, because activity data were national data instead of the plant-specific data.

Table 4.5. Summary of CO_2 emissions and emission factor in Jang et al. (2008).

Waste component	Amount of incineration (ton d^{-1})[a]					Water Content[b] (%)	Carbon content[b] (%)	Emissions (ton d^{-1})	EF (kg CO_2 t^{-1})	Reference
	MSW	Industry	Construction	Hazardous	Total					
Food	516	-	-	-	516	16	46.4	-	0	MSW
Paper	2624	94	-	-	2718	75.2	41.7	-	0	MSW+Industry
Wood	1223	629	75	-	1927	52.4	47.4	-	0	MSW+Industry+Construction
Rubber	540	-	-	-	540	96	54.5	-	0	MSW
Plastic	1185	3958	574	-	5717	61.8	72.8	9149	1650	MSW+Industry+Construction
Synthetic textile	-	100	-	-	104	74.5	72.8	200	1989	Industry
Synthetic rubber	-	140	3.3	-	140	99.9	72.8	363	2666	Industry
Synthetic leather	-	31	-	-	31	99.9	72.8	74	2506	Industry
Synthetic polymer	-	-	-	183	183	93.9	72.8	293	1650	Hazardous waste
Waste oil[c]	-	-	-	998	998	-	-	2852	2947	Hazardous waste
Sludge	-	1802	-	57	1859	26	23.5	-	0	Industry+Hazardous waste
Organic residual	-	58	-	-	58	16	46.4	-	0	Industry
Organic waste oil	-	1.2	-	-	1.2	100	66.9	-	0	Industry
Other[d]	1607	356	-	219	2182	60.5	50.9	1075	565	MSW+Industry+Hazardous

[a] NIER, 2006. 2005 Status of waste generation and disposal in Korea and 2005 Status of specified waste generation and disposal in Korea

[b] MOE, 2002. 2001 Status of waste generation statistics in Korea.

[c] Emission factor of waste oil was calculated by multiplying the gross calorific value by the CO_2 emission factor from 2006 IPCC guidelines.

[d] Domestic waste of food, paper, wood, rubber/leather, and synthetic resin.

In Kan et al. (2008) study, emission characteristics of CO_2 were studied in waste incineration. N_2O emission factors were based on MOE (2002). And CO_2 emission factors were not represented in the study. By 2020, CO_2 and N_2O emissions for MSW, industrial waste, construction waste, and specified waste sector according to business as usual (BAU), waste reduction policy, waste treatment policy for basic structure, and energy recovery in South Korea.

In Kim et al. (2010) study, CO_2 emission factor was calculated for MSW incineration facility of 200 tons/day, stoker type, and two incinerators operated by local authority. The NDIR was used for CO_2 measurement in flue gas. The waste component, dry matter content, and carbon content were measured, and the CO_2 emission was calculated by IPCC methodology of Tier 2b. The emission factor was calculated by dividing CO_2 emissions by the amount of incineration. Emission factors that take into account fossil carbon content of actual emissions from the flu gas were not presented in Kim et al. (2010) study. Therefore, the emission factor in 2009 calculated by the Tier 1 method of IPCC default values was 1060 kg CO_2/ton-waste and those by Tier 2b method was 960 kg CO_2/ton-waste.

In master's thesis of Lee (2012), estimations of CO_2 emissions were proposed in three methods from MSW and industrial waste facilities. The first estimation method was the emission measured from flue gas in the duct. The NDIR was used for CO_2 measurement in flue gas, which flow rate was calibrated with reverse correction of

oxygen due to TMS data of oxygen calibration. The second estimation method was the emission calculated by IPCC default values, which fossil carbon content and oxidation factor were values of IPCC default. In the third estimation method, CO_2 emission calculated from the ratio of the dry combustion gas to the calorific value generated during incineration (F) and the ratio of CO_2 gas production to the same calorific value (Fc). In addition, CO_2 emissions from flue gas and estimation of calorific value were recalculated by applying fossil carbon ratio from the parameters of waste component, dry matter content, and fossil carbon content. The fossil carbon ratio was calculated as the sum of plant without calculating each waste component. CO_2 emission result for three methods showed that the measured CO_2 emissions were similar to those estimated by calorific values from MSW and industrial waste facilities, but CO_2 emissions for IPCC default method (Tier 2b) were the highest. In MSW, the measured CO_2 emissions were lower than the estimated CO_2 emissions from calorific value, but the opposite in industrial waste facilities. Although there was no calculation of the emission factors, it was very meaningful to suggest how to estimate actual CO_2 emissions. In addition, since the flue gas sampled from ducts contained biological origin, the following equation was applied considering the fossil carbon content.

$$E_{end} = E_{initial} \times \frac{\sum_i (SW_i \times dm_i \times CF_i \times FCF_i)}{\sum_i (SW_i \times dm_i \times CF_i)} \quad (4.1)$$

Here, E_{end} was CO_2 emission originated from fossil carbon, $E_{initial}$ was CO_2 emission

originated from total carbon, i was municipal solid waste, industrial waste, sewage sludge and etc., SW was total amount of solid waste of type i, dm was dry matter content in the waste (wet weight) incinerated (fraction), CF was fraction of carbon in the dry matter, FCF was fraction of fossil carbon in the total carbon.

Another study that estimated CO_2 emissions by calorific value was done by Kim et al. (2011). The changes in total emissions from 1 to 5% for 5 items affecting emissions such as calorific value, dry matter content, hydrogen content, oxygen content, and sulfur content of incineration wastes were examined. Dry matter content showed the greatest effect, followed by oxygen content. Sulfur content and hydrogen content were not affected.

In study of Chen and Lin (2010), CO_2 emissions were calculated by IPCC default values (Tier 2a) and measuring from flue gas in the Taipei city in Taiwan. The CO_2 emission factor of measured emission was 964 kg CO_2/ton-waste and those of IPCC default values (Tier 2a) was 567 kg CO_2/ton-waste. Emission factor of measured emission was also higher than those of IPCC default values (Tier 2a), which this is because the biogenic carbon content was also included.

The values for waste fraction, dry matter content, and carbon content shows in Table 4.6 and 4.7 for Kim et al. (2010), MOE (2000), MOE (2002), and this study. In MOE (2000) and MOE (2002) study, CO_2 emission factors were calculated without considering fossil carbon content. Kim et al. (2010) presented CO_2 emission

factors by IPCC method of Tier 2a and Tier 2b. Emission factors were not calculated for actual measured emission from flue gas taking into account fossil carbon content. But CO_2 emission factors for each component were recalculated in this study from actual measured emissions from flue gas taking into account fossil carbon content. The fossil carbon content in the total carbon was 36% for A facility, 33% for B facility in this study, and 35% in Kim et al. (2010) using the equation 4.1. The plastics showed the highest fossil carbon content, followed by vinyl and rubber, textiles, inert waste, and paper. And the CO_2 emission factors for each waste component were similar in Kim et al. (2010) and this study. The range of CO_2 emission factors in MSW ranged from approximately 130 to 1060 kg CO_2/ton-waste. The reason for the large deviation was that in this study, the average value of total carbon content was calculated from the actual measured emissions using total average fossil carbon content, Kim et al. (2010) estimated the emission factors from the emissions calculated by IPCC method (Tier 2a and Tier 2b), and MOE (2000, 2002) used carbon content not fossil carbon content, which overestimated for CO_2 calculation of emission factors.

In NIR of Japan (2017), CO_2 emissions in MSW were estimated by plastics, synthetic textile, paper (and cardboard from fossil fuel derived), and nappy (fossil fuel derived), which used parameters of calculation for biogenic origin ratio to considering fossil carbon origin and only domestic products. But in studies of Korea, all waste components included other material components, for example, Korean

paper for waste contained nappies, while Japanese nappy contained no paper. The Ministry of Environment (MOE) conducts an annual survey on the status of waste generation and disposal nationwide, and the components of wastes are slightly different from that of Japan. As with the nappy described above, textiles are classified as industry waste, but are not classified as MSW because of recycling, which in fact, textiles are more than 3% of MSW in Table 4.6. Therefore, the emission factor variation may be large depending on such waste components, and it was affected by various parameters by methodologies, operation types of incinerators, condition of operation, measuring method for equipment, etc. Therefore, national emission factors need to be developed for waste component and operation type based on the more emission factors from plant-specific data.

The CH_4 and N_2O emission factors in MSW in this study were reversed depending on the denitrification system, and MOE (2000) showed that CH_4 emission factors varied considerably depending on the operation types. N_2O emission factors varied widely depending on operation types, denitrification system, and equipment type. The CH_4 emission factors in MSW range from approximately 0.36 to 409 g CH_4/ton-waste, and those of N_2O range from approximately 5 to 134 g N_2O/ton-waste which were large deviations, and many studies have not been conducted in Korea. Like CO_2 emission factor, it was affected by various parameters by methodologies, operation types of incinerators, condition of operation, measuring method for equipment, etc. Therefore, national emission factors need to be

developed for waste component and operation type based on the more emission factors from plant-specific data.

Emission factors for specified waste studied in Korea were from MOE (2002) and this study. MOE (2000) showed that the emission factors for the moving grate & rotary kiln were different pattern from the stoker & Spray combustion incineration facilities according to greenhouse gases. Emission factors were not presented except MOE (2002) and this study. In Japan, CO_2 emission factors for four waste items were presented, but CH_4 and N_2O emission factors used industrial waste ones. Furthermore, the N_2O emission factor of industrial waste in NIR of Korea also used in construction and specified waste, and CH_4 emissions were not calculated in all kinds of waste facilities because of methodology of GPG 2000 related with negligible gas. Therefore, further studies on the estimation of future emission factors would be necessary. And in GPG 2000, CH_4 emissions and emission factors should be added in NIR of Korea.

In this study, four times sampling from October 2006 to July 2007 showed little seasonal effect on the changes in CO_2, CH_4, and N_2O gas emissions from flue gas, which the efficiency of incineration was more than 99%. However, MOE (2002) study showed that moisture content was influenced by season, which in case of small incinerators, it is necessary to consider incineration efficiency.

Table 4.6. Waste fraction, dry matter content, and carbon content in MSW.

	Kim et al. (2010)[c]			MOE (2000)			MOE (2002)			This study		
Waste component	WF	dm	CF	WF	dm	CF	WF L/M/S[f]	dm	CF	WF A/B[i]	dm	CF
Paper[a]	0.43	0.786	0.391	0.31	0.77	0.5	0.26/0.33/0.13	46.4[g] /	0.4/0.42/0.41	0.32/0.369	0.59	0.51
Textile	0.031	0.716	0.482				0.05/0.26/0.3	17.9 [g]/	0.49/0.56/0.53	0.032/0.065	0.7	0.8
Food	0.041	0.327	0.443	0.24	0.28	0.52	0.33/ND/ND[h]	12.6[g]	0.42/ND/ND	0.2/0.266	0.55	0.44
Wood	0.045	0.853	0.482	0.13	0.79	0.54	0.09/0.31/0.41		0.46/0.5/0.53	0.092/0.043	0.75	0.48
Garden[b]												
Nappies												
Rubber[b]	0.016	1	0.671	0.04	0.88	0.68	0.001/0.01/0.02		ND/ND/0.57	0.091/0.069	0.76	0.77
Plastics	0.377	0.984	0.686	0.1	0.86[e]	0.8	0.22/0.1/0.12		0.68/0.68/0.64	0.195/0.147	0.76	0.77
Metal	0.016	1										
Glass	0.015	1		0.16[d]								
Other, inert waste	0.056	0.867	0.02	0.01			4.3		0.04/ND/ND	0.071/0.041	0.9[j]	0.03 [j]

[a] Paper and cardboard waste.

[b] Garden/Yard, park waste. And rubber and leather

[c] Based on 2009.

[d] It was a value for other flammability.

[e] The value was combined with MSW, industry, and construction waste

[f] 'L' was large incinerator (over 2 ton/hr), 'M' was medium incinerator (0.2~2ton/hr), and 'S' was small incinerator (less than 0.2 ton/hr) for the amount of incineration. And it was the average of four seasons.

[g] It was the average value of all waste components.

[h] No data.

[i] A and B facilities.

[j] 2006 IPCC default value.

Table 4.7. Emission factors (EF) of waste incineration from other studies.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
Korea (continuous incineration)						
This study	MSW, Stoker	SCR	137	154	5	Using total FCF
	Food		0			Using each FCF component
	Paper		8			(CO_2: dry basis)
	Wood		0			(CH_4/N_2O: wet basis)
	Textiles		17			
	Vinyl/rubber		85			
	Plastics		915			
	Inert waste		15			
	MSW, Stoker	SNCR	131	21	134	Using total FCF
	Food		0			Using each FCF component
	Paper		4			(CO_2: dry basis)
	Wood		0			(CH_4/N_2O: wet basis)
	Textiles		97			
	Vinyl/rubber		168			
	Plastics		838			
	Inert waste		39			
	CSW, Fluidized bed	SCR		23	260	
	Specified waste:	SNCR				
	Kiln & stoker		2,647	55	730	
	Stoker		3,190	76	583	
	Moving grate		3,434	-	168	
	Rotary kiln			84	193	

Table 4.7. Continued.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
Park et al. (2011)	MSW, Stoker	SCR			71	
	Stoker	SNCR			75	
	Kiln & stoker	SCR			153	
Jang et al. (2008)			565			See Table 4.5
Kim et al. (2010)	MSW, Stoker	SCR	1,060			Tier 2a
			960			Tier 2b
	Food		0			Recalculated in this study
	Paper		4			(See Table 4.6)
	Wood		0			
	Textiles		89			
	Vinyl/rubber		174			
	Plastics		874			
	Inert waste		22			
MOE (2016)			IPCC default			CH_4/N_2O: Korea guidelines
	MSW			6.1	52.1	
	Industrial waste[a]			13.9[a]	129.7	
	Sewage sludge			76.3	595	
Korea (NIR)			GPG 2000			
	MSW				52.1	
	Industrial waste				129.7	Construction, Specified waste
	Sewage sludge				595	

Table 4.7. Continued.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
MOE (2000)[j]	MSW, Stoker		507		90	See Table 4.6 (Total CF)
	Vinyl/rubber		2092			(Each CF)
	Industrial waste		828		149[h]	
	Plastics		2347			MSW+Industry+Constrction
	Texitles		1408			
	Rubber		2299			
	Leather		1874			
	Polymers		2347			
	Fluidized bed[i]		1273		454	
	Dry distillation type		1897		43	
	Rotary kiln		2072		36	
	Construction waste		794			
	Fluidized bed		344		189	
	Pre-mixing		320		458	
MOE (2002)[k]	MSW, Stoker (L: large)		350	0.36	21.36	
	Fluidized bed (M: medium)		730	409	68.6	
	Fluidized bed (S: small)		380		29.43	
	Industrial waste					
	Stoker (M)		490	327	19.02	
	Fluidized bed (S)		1000	19	299.18	
	Specified waste					
	Moving grate/Rotary kiln (L)		240	35.3	45.48	No sludge
					408.42	Sludge
	Stoker/Spray combustion (M)		1070	5.8	121.56	

Table 4.7. Continued.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
Other countries and researches						
Harris et al. (2015)	Mean of MSW and industry	SCR			4.3	Continuous incineration
		SNCR			51.5	
2006 IPCC: MSW			IPCC default			CO_2: Table 4.4
	Continuous and semi-continuous incinerators				50	CH_4/N_2O: wet weight
	Batch type incinerators				60	
	Open burning				150	Dry weight
Japan (GIO, 2004)	Continuous, stoker			0.2	47	
	Fluidized bed			0	67	
	Semi-continuous, stoker			6	41	
	Fluidized bed			188	68	
	Batch type, stoker			60	56	
	Fluidized bed			237	221	
Germany					8	
Netherlands					20	
Austria					12	

Table 4.7. Continued.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
2006 IPCC: Sludge and industrial waste						
Industrial waste (all types of incineration)					100	
Sludge (except sewage sludge)					450	
Sewage sludge					990	Dry weight
					900	Wet weight
Japan (GIO, 2005)	Waste paper/wood				10	
	Waste oil				9.8	
	Waste plastics				170	
	Sludge (except sewage sludge)				450	
	Dehydrated sewage sludge				900	
	High molecular weight flocculant				1,508	fluidized bed incinerator at normal temperature
	High molecular weight flocculant				645	fluidized bed incinerator at high temperature
	High molecular weight flocculant				882	multiple hearth
	Other flocculant				882	
	Lime sludge				294	
Germany	Sewage sludge				990	Dry weight
	Industrial waste				420	
Germany (NIR)	Energy sector					Energy recovery (WTE)
U.S.A. (NIR)	Energy sector					Energy recovery (WTE)

Table 4.7. Continued.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
Japan (NIR, 2017)	MSW					(CO_2: dry basis)
2015 based	Plastics		2,754			
	Synthetic textile		2,310			
	Paper/cardboard		17			Fossil fuel derived
	Nappy		257			Fossil fuel derived
	Plastic bottles		2,292			Not adopted to estimate CO_2 emissions
	Continuous incinerator			2.7	38.1	(CH_4/N_2O: wet basis)
	Semi-continuous incinerator			21.1	73.5	
	Batch type incinerator			11.7	76.2	
	Gasification melting furnace			6.9	12.0	
	Industrial waste					Wet basis
	Waste oil		2,933	4.8[b]/4.0[c]	12 [b]/62 [c]	
	Plastics		2,567	3.0/8.0	180/15	
	Paper/cardboard		17	22/22.5	21/77	CO_2: dry basis
	Wood			22/22.5	21/77	
	Textile (natural fiber)			22/22.5	21/77	
	Animal and Vegetable residues/animal carcasses			22/22.5	21/77	
	Sludge			14/1.5	457/99	
	Other than sewage sludge					
	Sewage sludge					
	Fluidized bed incinerator[d]				1,508	Around 800˚C
					645	Around 850˚C
	Multiple hearth[d]				882	

Table 4.7. Continued.

	Type of plant	De-NO_x system	CO_2 (kg CO_2 t^{-1})	CH4 (g CH_4 t^{-1})	N_2O (g N_2O t^{-1})	Reference
Japan (NIR, 2017)	Other				882	
2015 based	Lime sludge				294	
	Fluidized bed/ two-stage/stoker[e]				263	Around 850˚C
	Carbonization furnace[f]					
	Specially-controlled waste[g]					Wet basis
	Flammable waste oil		2,933			
	Specified hazardous industrial waste oil		1,024			
	Infectious plastics		2,567			

[a] Industrial waste was contained from waste of workplace, specified waste, and construction waste.

[b] FY 1990-2001: Fiscal year was from April of the reporting year through March of the next year.

[c] FY 2002 onward.

[d] FY 2002 High-molecular weight flocculant.

[d] Multiple hearth air injection incineration method fluidized bed incinerator, two-stage incineration method circulating fluidized bed incinerator, and stoker furnace.

[f] Carbonization furnace for solid fuel production.

[g] CH_4 and N_2O emission factors for industrial waste were used for specified waste.

[h] Industrial waste EF was the average value, and EF of N_2O was the total average value of industry(No sludge) and construction waste.

[i] EF was the average value of facility (195 kg/hr capacity) and (3000 kg/hr capacity).

[j] Biogenic origin waste was calculated to have no fossil carbon content such as food, paper, and wood. And carbon content was regarded as fossil carbon content in MOE (2000).

[j] Incineration was classified as large (over 2 ton/hr), medium (0.2~2ton/hr), and small (less than 0.2 ton/hr) for the amount of incinerator.

4.4 Conclusions

An overview of the emission factors for wastewater treatment and incineration facilities in various countries are presented in this study.

Emission factors in wastewater treatment facilities vary greatly by country, process, and types of anaerobic or aerobic process. The main reason is that there may be differences in the degradable materials into the sewage plant, depending on the degree of anaerobic decompositions. These deviations of emission factors largely depend on the treatment processes, the presence of the sludge digester, and the emission factor measurement unit of BOD or COD basis. For these reasons, it is necessary to determine the national emission factors by estimating the plant-specific emission factors. The CH_4 emission factors in WWTP ranges from approximately 3 to 21 g CH_4/kg BOD_5, and that of N_2O ranges from approximately 1 to 28 g N_2O/kg TN. In MOE (2000) study, B_o presented by IPCC guidelines should be 0.6 kg CH_4/kg BOD, but there was an error using 0.25 kg CH_4/kg BOD for default value. In the MOE (2002) study, sampling basins were missing in aeration and secondary settlement basins, and the emission factor was overestimated because two plants included manure treatment. MOE (2002) study also missed sampling in sludge thickener.

The emission factors of incineration facilities also vary widely by country, process types, and de-NO_x systems. Since the national emission factor is the average

of each plant emission factor, it is considered to be most important to measure the emission factors of the unique plant specific data.

However, the measurement of emission factor in wastewater treatment facilities is limited because of the various treatment types at each plant. In other words, in the sedimentation basin, aeration basin, and sludge thickener, covering with a roof to prevent the generation of odor for odor prevention law, so it may be impossible to use the chamber method for measuring the GHG emissions. Furthermore, in the incineration facilities, even if the emission factor of each plant is measured, the incinerator is often worn and replaced with the incinerator of the latest specification. In such cases, the national emission factors shall be changed by applying the emission factors of each plant measured on the basis of the replacement incinerator.

In chapter 3, the CO_2 emission factor in MSW was presented as a whole average value, but in this chapter, the CO_2 emission factors were calculated according to each waste component. It was necessary to develop the CO_2 emission factors according to waste components rather than the average value because of the difference and deviation. The emission factors showed a large deviation in studies. Kim et al. (2010) estimated the emission factors from the emissions calculated by IPCC method (Tier 2a and Tier 2b), and MOE (2000, 2002) used carbon content not fossil carbon content, which overestimated for CO_2 calculation of emission factors.

Furthermore, the N_2O emission factor of industrial waste in NIR of Korea also used in construction and specified waste, and CH_4 emissions were not calculated in

all kinds of waste facilities because of methodology of GPG 2000 related with negligible gas. Therefore, further studies on the estimation of future emission factors would be necessary. And in GPG 2000, CH_4 emissions and emission factors should be added in NIR of Korea. Therefore, there are many limitations in estimation the emission factors for each plant, but it should be the basis for the national emission factors by estimating emission factors from plant-specific data.

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Chapter 5. Conclusions

Greenhouse gases are emitted in various sectors and numerous studies have been conducted on the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from various sources, which one of the sectors is waste. There is an increasing need to reduce these emissions and to identify the factors controlling the GHG emissions from wastewater treatment plants and incineration facilities. CO_2 emissions are biogenic origin source, thus should be excluded from the total emissions, whereas CH_4 and N_2O emissions should be contained in total emission inventory in wastewater sector. In this study, CH_4 and N_2O emissions were investigated from the Jungryang municipal wastewater treatment plant in Seoul to calculate the emission factors from each basin, including the wastewater sludge anaerobic digestion and anaerobic/anoxic/aerobic (A_2O) processes, which wastewater treatment processes are the pretreatment, primary treatment, secondary treatment and tertiary treatment. CH_4 and N_2O fluxes were estimated from each processing unit using a flux chamber system. Methane fluxes and emission factors from the sludge thickener have been the highest values except for sludge digestion tank. CH_4 flux from the sludge thickener was also measured up to approximately 3.5 times higher than the secondary settling basin. Also, the sludge thickener produced the highest CH_4 emissions, and the aeration basin had the highest N_2O emissions, excluding the sludge digestion tank. The N_2O emission factor of the sludge digestion

tank was lower than that of CH_4, which is used as recyclable energy and deducted from total GHG emissions. The total N_2O and CH_4 emission factors from the activated-sludge process were 1.256 ± 0.5 g N_2O/kg TN and 3.734 ± 1.21 g CH_4/kg BOD_5, respectively. The total N_2O and CH_4 emission factors from the advanced treatment were 1.605 ± 0.15 g N_2O/kg TN and 4.022 ± 0.12 g CH_4/kg BOD_5, respectively. The N_2O and CH_4 fluxes from the sludge digestion tank were 0.012 ± 0.01 g N_2O/kg TN and 227.0 ± 23.53 g CH_4/kg BOD_5, respectively.

In addition, CH_4 and N_2O emissions in the sewage treatment facilities are calculated by BOD basis of input activities during the microbial treatment of wastewater. The anaerobic digestion tank for sludge treatment is a reactor for treating sludge by anaerobic bacteria under anaerobic conditions, which is inconsistent with the BOD basis for oxygen demand bacteria. Therefore, it is necessary to further study the emission calculation formula in the sewage treatment facilities in the future.

Furthermore, nine waste incineration plants were measured for estimating GHGs to calculate of emission factors in flue gas, i.e. two incinerators of municipal solid waste (MSW), one incinerator of commercial solid waste (CSW) and six incinerators of specified waste, which were operated in various operation types such as stoker, kiln & stoker, fluidized bed, rotary kiln, etc., and different NO_x removal type. In chapter 3, the CO_2 emission factor in MSW was presented as a whole average value, but in this chapter, the CO_2 emission factors were calculated

according to each waste component. It was necessary to develop the CO_2 emission factors according to waste components rather than the average value because of the difference and deviation. The range of CO_2 emission factors in MSW ranged from approximately 130 to 1060 kg CO_2/ton-waste. The reason for the large deviation was that in this study, the average value of total carbon content was calculated from the actual measured emissions using total average fossil carbon content, Kim et al. (2010) estimated the emission factors from the emissions calculated by IPCC method (Tier 2a and Tier 2b), and MOE (2000, 2002) used carbon content not fossil carbon content, which overestimated for CO_2 calculation of emission factors. The CH_4 emission factors in MSW range from approximately 0.36 to 409 g CH_4/ton-waste, and those of N_2O range from approximately 5 to 134 g N_2O/ton-waste which were large deviations, and many studies have not been conducted in Korea. The emission factor was affected by various parameters by methodologies, operation types of incinerators, condition of operation, measuring method for equipment, etc. Therefore, national emission factors need to be developed for waste component and operation type based on the more emission factors from plant-specific data. Furthermore, the N_2O emission factor of industrial waste in NIR of Korea also used in construction and specified waste, and CH_4 emissions were not calculated in all kinds of waste facilities because of methodology of GPG 2000 related with negligible gas. Therefore, further studies on the estimation of future emission factors would be necessary. And in GPG 2000, CH_4 emissions

and emission factors should be added in NIR of Korea.

Therefore, in order to make national emission factors, it is necessary to estimate country-/plant-specific emission factors for each country to estimate emissions because it affects GHG emissions by site, region, and country depending on the type of operation, operating conditions, and other technologies. Furthermore, it is necessary to develop emission factors according to the waste components for incineration facilities. And it is needed to further study the mechanism of the anaerobic digestion tank during the sewage treatment process and revise the emission formula. GHG emission factors obtained by this study will be helpful for providing country-specific data and national emission factors in the wastewater and incineration sector in Korea.

Appendix

Wastewater can be a source of methane (CH_4) and nitrous oxide (N_2O) when treated or disposed anaerobically. Carbon dioxide (CO_2) emissions from wastewater are not considered in the IPCC Guidelines because these are of biogenic origin and should not be included in national total emissions. The general equation to estimate CH_4 emissions from domestic wastewater of 2006 IPCC guidelines is as follows:

$$CH_4 \text{ Emissions} = [\sum_{i,j}(U_i \times T_{i,j} \times EF_j)](TOW - S) - R \qquad (5.1)$$

Where:

CH_4 Emissions = CH_4 emissions in inventory year, kg CH_4/yr

TOW = total organic in wastewater in inventory year, kg BOD/yr

S = organic component removed as sludge in inventory year, kg BOD/yr

U_i = fraction of population in income group *i* in inventory year

$T_{i,j}$ = degree of utilization of treatment/discharge pathway or system, *j*, for each income group fraction *i* in inventory year

i = income group: rural, urban high income and urban low income

j = each treatment/discharge pathway or system

EF_j = emission factor, kg CH_4 / kg BOD

R = amount of CH_4 recovered in inventory year, kg CH_4/yr

The equation for emission factor is:

$$EF_j = B_o \times MCF_j \quad (5.2)$$

Where:

EF_j = emission factor, kg CH_4/kg BOD

j = each treatment/discharge pathway or system

B_o = maximum CH_4 producing capacity, kg CH_4/kg BOD

MCF_j = methane correction factor (fraction)

The equation for TOW is:

$$TOW = P \times BOD \times 0.001 \times I \times 365 \quad (5.3)$$

Where:

TOW = total organics in wastewater in inventory year, kg BOD/yr

P = country population in inventory year, (person)

BOD = country-specific per capita BOD in inventory year, g/person/day

0.001 = conversion from grams BOD to kg BOD

I = correction factor for additional industrial BOD discharged into sewers

(for collected the default is 1.25, for uncollected the default is 1.00.)

The simplified general equation to estimate CH_4 emissions from domestic wastewater of GPG 2000 is as follows:

CH_4 Emissions =

$$(\text{Total Organic Waste} \times \text{Emission Factor}) - \text{Methane Recovery} \qquad (5.4)$$

The quick estimation method is as follows:

$$\text{WM} = \text{P} \times \text{D} \times \text{SBF} \times \text{EF} \times \text{FTA} \times 365 \times 10^{-12} \qquad (5.5)$$

Where:

WM = Annual CH_4 emission per country, from domestic wastewater (Tg)

P = Population of country or urban population for some developing countries (person)

D = Organic load in biochemical oxygen demand per person (g BOD/person/day), overall default = 60 g BOD/person/day

SBF = Fraction of BOD that readily settles, default = 0.5

EF = Emission factor (g CH_4/g BOD), default = 0.6

FTA = Fraction of BOD in sludge that degrades anaerobically, default = 0.8

$$\text{Emission Factor} = B_o \times \text{Weighted Average of MCFs} \qquad (5.6)$$

Where:

B_o = Maximum methane producing capacity, default value of 0.25 kg CH_4/kg COD or a default value of 0.6 kg CH_4/kg BOD

MCF = Methane conversion factor (fraction)

The general equation to estimate N_2O emissions from domestic wastewater of 2006 IPCC guidelines is as follows:

$$N_2O\ Emissions = N_{EFFLUENT} \times EF_{EFFLUENT} \times 44/28 \quad (5.7)$$

Where:

N_2O emissions = N_2O emissions in inventory year, kg N_2O/yr

$N_{EFFLUENT}$ = nitrogen in the effluent discharged to aquatic environments, kg N/yr

$E_{FEFFLUENT}$ = emission factor for N_2O emissions from discharged to wastewater, kg N_2O-N/kg N

The factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

$$N_{EFFLUENT} = (P \times Protein \times F_{NPR} \times F_{NON-CON} \times F_{IND-COM}) - N_{SLUDGE} \quad (5.8)$$

Where:

$N_{EFFLUENT}$ = total annual amount of nitrogen in the wastewater effluent, kg N/yr

P = human population

Protein = annual per capita protein consumption, kg/person/yr

F_{NPR} = fraction of nitrogen in protein, default = 0.16, kg N/kg protein

$F_{NON-CON}$ = factor for non-consumed protein added to the wastewater

$F_{IND-COM}$ = factor for industrial and commercial co-discharged protein into the sewer system

N_{SLUDGE} = nitrogen removed with sludge (default = zero), kg N/yr

The equation for N_2O emission from centralized wastewater treatment process is:

$$N_2O_{PLANTS} = P \times T_{PLANT} \times F_{NON-CON} \times EF_{PLANT} \quad (5.9)$$

Where:

N_2O_{PLANTS} = total N_2O emissions from plants in inventory year, kg N_2O/yr

P = human population

T_{PLANT} = degree of utilization of modern, centralized WWT plants, %

$F_{IND-COM}$ = fraction of industrial and commercial co-discharged protein (default = 1.25, based on data in Metcalf & Eddy (2003) and expert judgment)

E_{FPLANT} = emission factor, 3.2 g N_2O/person/year

Tier 1 concept is that CH_4 and N_2O emissions can be estimated using default emission factors by 2006 IPCC guidelines (B_o (maximum CH_4 producing capacity), MCF (methane correction factor), etc.). Tier 2 concept is that CH_4 and N_2O emissions can be estimated using country-specific emission factors (B_o, MCF, etc.). Tier 3 is that CH_4 and N_2O emissions can be estimated using bottom-up data, i.e. plant-specific emission factors.

Emissions from waste incineration without energy recovery are reported in the Waste Sector, while emissions from incineration with energy recovery are reported in the Energy Sector, both with a distinction between fossil and biogenic carbon dioxide (CO_2) emissions (IPCC, 2006). CO_2 emissions from oxidation, during incineration in waste of fossil carbon (such as plastics, certain textiles, rubber, liquid solvents, and other fossil materials) are considered net emissions for CO_2 emission estimate, while those of biomass materials (such as paper, food, and wood waste) should not be included in total emissions. CO_2 emission estimate based on the total amount of waste combusted is as follows:

$$CO_2\ Emissions = \sum_i (SW_{i,j} \times dm_{i,j} \times CF_{i,j} \times FCF_{i,j} \times OF_{i,j}) \times 44/12 \quad (5.10)$$

Where:

CO_2 Emissions = CO_2 emissions in inventory year, Gg/yr

SW_i = total amount of solid waste of type *i* (wet weight) incinerated, Gg/yr

dm_i = dry matter content in the waste (wet weight) incinerated, (fraction)

CF_i = fraction of carbon in the dry matter (total carbon content), (fraction)

FCF_i = fraction of fossil carbon in the total carbon, (fraction)

OF_i = oxidation factor, (fraction)

44/12 = conversion factor from C to CO_2

i = type of waste incinerated specified

j = component of the MSW incinerated such as paper/cardboard, textiles, food waste, wood, garden (yard) and park waste, disposable nappies,

rubber and leather, plastics, metal, glass, other inert waste.

Tier 1 for CO_2 concept is that CO_2 emissions can be estimated using default data on emission factors by 2006 IPCC. Tier 2a concept is that CO_2 emissions can be estimated using country-specific and default emission factors. Tier 2b is that CO_2 emissions can be estimated using country-specific and emission factors. Tier 3 is that CO_2 emissions can be estimated using plant-specific emission factors.

Table 5.1. Default values of dry matter content, total carbon content and fossil carbon fraction of different MSW components (IPCC, 2006)

MSW component	Dry matter content in % of wet weight	Total carbon content in % of dry weight		Fossil carbon fraction in % of total carbon	
	Default	Default	Range	Default	Range
Paper/cardboard	90	46	40–50	1	0–5
Textiles	80	30	25–50	20	0–50
Food waste	40	38	20–50	-	-
Wood	85	50	46–54	-	-
Garden/Yard and Park waste	40	49	45–55	0	0
Nappies	40	60	44–80	10	10
Rubber and Leather	84	47	47	20	20
Plastics	100			100	90–100
Metal	100			NA	NA
Glass	100			NA	NA
Other, inert waste	90			100	50–100

Table 5.2. Overview of data sources of different CO_2 tier levels (IPCC, 2006)

Data Sources / Tiers	Total waste Amount (W)	Waste fraction (WF, %)	Dry matter Content (CF)	Carbon fraction (CF)	Fossil carbon fraction (FCF)	Oxidation factor (OF)
Tier 3	plant-/ management specific	plant-/ management specific	plant-/ management specific	plant-/ management specific	plant-/ management specific	plant-/ management specific
Tier 2b	country-specific	country-specific	country-specific	country-specific	default/ country-specific	default/ country-specific
Tier 2a	country-specific	country-specific	default	default	default	default
Tier 1	default/ country-specific	default	default	default	default	default

Fossil liquid waste for incineration is considered as industrial and municipal residues such as mineral oil, natural gas or other fossil fuels. The equation is as follow:

$$CO_2\ Emissions = \sum_i AL_i \times CL_i \times OF_i \times 44/12 \quad (5.11)$$

Where:

CO_2 Emissions = CO_2 emissions from incineration of fossil liquid waste, Gg

AL*i* = amount of incinerated fossil liquid waste type *i*, Gg

CL*i* = carbon content of fossil liquid waste type *i*, (fraction)

OF_i = oxidation factor for fossil liquid waste type *i*, (fraction)

44/12 = conversion factor from C to CO_2

In GPG 2000, incinerator efficiency was added instead of dry matter content. The equation is as follow:

$$CO_2\ Emissions\ (\frac{Gg}{yr}) = \sum_i (IW_i \times CCW_i \times FCF_i \times EF_i) \times 44/12 \quad (5.12)$$

Where:

i = MSW: municipal solid waste

HW: hazardous waste

CW: clinical waste

SS: sewage sludge

IW_i = Amount of incinerated waste of type i (Gg/yr)

CCW_i = Fraction of carbon content in waste of type i

FCF_i = Fraction of fossil carbon in waste of type i

EF_i = Burn out efficiency of combustion of incinerators for waste of type i (fraction)

44/12 = Conversion from C to CO_2

Table 5.3. Default data for CO_2 from incineration (GPG, 2000)

	MSW	Sewage Sludge	Clinical Waste	Hazardous Waste
C Content of Waste	33–50% of waste (wet) default: 40%	10–40% of sludge (dry matter) default: 30%	50–70% of waste (dry matter) default: 60%	1–95% of waste (wet) default: 550%
Fossil Carbon as % of Total Carbon	30–50% default: 40%	0%	30–50% default: 40% more information is needed	90–100% default: 90%
Efficiency of Combustion	95–99% default: 95%	95%	50–99.5% default: 95%	95–99.5% default: 99.5%

Methane and nitrous oxide emissions from incineration are generated in the incomplete combustion and usually very small. CH_4 emission estimate based on the amount of waste combusted is as follows:

$$CH_4 \; and \; N_2O \; Emissions = \sum_i (IW_{i,j} \times EF_{i,j}) \times 10^{-6} \qquad (5.13)$$

Where:

CH_4 and N_2O Emissions = CH_4 and N_2O emissions in inventory year, Gg/yr

IW = amount of solid waste of type *i* incinerated or open-burned, Gg/yr

EF = aggregate CH_4 and N_2O emission factor, kg CH_4 and N_2O/Gg of waste

10^{-6} = conversion factor from kilogram to gigagram

i = category or type of waste incinerated

j = component of the MSW incinerated such as paper/cardboard, textiles, food waste, wood, garden (yard) and park waste, disposable nappies, rubber and leather, plastics, metal, glass, other inert waste.

Tier 3 for N_2O emissions estimate based on influencing factors is as follows:

$$N_2O \; Emissions = \sum_i (IW_i \times EC_i \times FGV_i) \times 10^{-9} \qquad (5.14)$$

Where:

N_2O Emissions = N_2O emissions in inventory year, Gg/yr

IW_i = amount of incinerated waste of type *i*, Gg/yr

EC_i = N_2O emission concentration in flue gas from the incineration of waste type *i*, mg N_2O/m^3

FGV_i = flue gas volume by amount of incinerated waste type *i*, m^3/Mg

10^{-9} = conversion to gigagram

i = category or type of waste incinerated

Tier 1concetp is that CH_4 and N_2O emissions can be estimated using default data on emission factors by 2006 IPCC. Tier 2 is that CH_4 and N_2O emissions can be estimated using country-specific data. Tier 3 is that CH_4 and N_2O emissions can be estimated using plant- or management practice-specific emission factors.

국문초록

폐기물 부문 중 하수처리시설 및 소각시설에서의 온실가스 배출계수 개발

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지구 온난화와 기후 변화는 현재 중요한 과학적, 경제적 그리고 정치적 문제로 대두되었다. 기후 변화에 관한 정부간 패널 (IPCC)에서 2014년 발간한 제 5차 평가보고서(AR5)에 따르면, 과학자들은 지구 온난화가 주로 인위적 활동에 의해 야기되고 있으며 화석 연료 연소, 관개, 삼림 벌채 등으로 인하여 온실가스의 대기 중 농도는 1850년 이후 약 25% 증가했다고 보고하고 있다.

유엔의 온실가스 감축활동과 더불어 우리나라 또한 온실가스 감축 활동을 위해 2010년 제정된 저탄소 녹색 성장 기본법을 선두로 정치, 경제 및 사회 부문에서 다양한 활동을 추진하고 있으며, 2015년에는 우리나라 온실가스 감축목표를 배출전망치 대비 37% 감축하는 것으로

결정하기도 하였다. 또한 국가 온실가스 인벤토리(통계)보고서 (NIR: National Inventory Report)를 기후 변화 협약 (UNFCCC)에 제출하고 있으며, 현재 온실가스 감축을 위하여 목표관리제도와 배출권거래제도를 시행하고 있다. 이러한 온실가스 배출량을 산정하기 위해서는 각 분야별 배출계수가 필요하며 각 사업장별 (Tier 3), 국가별 (Tier 2) 그리고 IPCC 배출계수 (Tier 1)을 적용하여 배출량을 산정하고 있다. 그러나 폐기물 분야에서의 배출계수에 대한 개발이 부족한 실정으로 본 연구에서는 하수처리시설과 소각시설에서의 사업장 별 배출계수를 개발하였다.

첫 번째 연구에서는 하수처리시설에서의 각 반응조에 따른 온실가스 배출계수를 산정하였다. 하수처리시설의 이산화탄소 배출은 생물 기원으로 총 배출량 산정에서 제외하고 있으므로 메탄 및 아산화질소에 대한 배출계수를 산정하였다. 온실가스 샘플링 작업은 제 1차 침전조, 포기조, 제 2차 침전조, 농축조, 슬러지 소화조 그리고 고도처리시설 (A^2O)에서 이루어졌으며, 각 조별 배출량 및 배출계수를 산정하였다. 또한 하수처리서설의 온실가스 배출계수 산정은 생물화학적 산소 요구량 (BOD)에 따라 산정하고 있으나, 슬러지 처리를 위한 혐기성 소화조의 경우 혐기성 상태에서 혐기성 박테리아의 활동으로 인한 메탄 생성 소화조이므로 산소를 필요로 하는 다른 반응조와 다른 메커니즘을 가지고 있으므로 혐기성 소화조의 배출계수에 대하여 향후 추가적인 연구가 필요할 것으로 판단된다.

두 번째 연구에서는 지자체에서 운영하는 생활 폐기물 소각장,

사업장 폐기물 소각장 그리고 지정 폐기물 처리 소각장에서의 배출계수를 산정하였다. 소각시설에서의 온실가스 배출량은 특히 소각로 방식(로타리 킬른, 스토커, 유동상 등), 배연 탈황/탈질 설비, 운영 조건, 운영 방식 등에 따라 큰 편차를 보이고 있다. 따라서, 소각시설의 경우 특히 각 사업장별 배출계수를 개발할 필요가 있다.

결론적으로 본 논문에서는 하수처리시설 및 소각시설에서 온실가스를 측정하여 실측에 의한 배출량 및 배출계수를 산정하였으며, 현재 하수처리 및 폐기물 소각시설에서의 국가 배출계수에 대한 오류가 있어 이를 수정할 필요가 있으며, 본 연구에서 개발한 배출계수는 향후 우리나라 국가 배출계수 개발에 의미 있는 자료로 사용될 것으로 기대된다.

주요어: 온실가스, 이산화탄소, 메탄, 아산화질소, 하수처리시설, 소각시설

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